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SURFACE CHARGE KINETICS NEAR METAL-DIELECTRIC INTERFACES EXPOSED TO KILOVOLT ELECTRON FLUX

(NASA-CR-155195) SURFACE CHARGE KINETICS NEAR METAL-DIELECTRIC INTERFACES EXPOSED TO KILOVOLT ELECTRON FLUX Final Report (Pennsylvania State Univ.) 65 p HC A04/MF A01 CSCL 09C G3/33

N77-33411

Unclas 50858

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NASA Grant No. NSG-3097

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ABSTRACT

Interfaces between dielectric films and grounded metallic boundaries have been exposed, in vacuum, to monoenergic electron fluxes having energies up to 22 keV. Two principal concerns have been the measuring of the charge distributions on dielectrics and the determining of causes of flashovers, events where dielectric surface charges abruptly transfer to the metallic structures. Surface charges are perturbed within 10 mm of interfaces, though in different ways by exposed metal substrates and by metal aperture plates. Perturbations are relatively small except within about 3 mm of the interface. The probability of flashover is not found to be related to charge gradients near interfaces but rather to microscopic imperfections in the interfaces. Slits in a specimen which expose a metal substrate do not necessarily cause frequent flashovers at first. However, as flashovers occur, trigger points will become burned into the dielectric along the slit. As these points develop, the probability of flashover increases greatly. An interface which is highly immune to flashover is formed by covering a dielectric film with a 1.5-mm-thick aperture plate which exposes the film through a machined opening.

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INTRODUCTION

Exposed surfaces of a spacecraft are subjected to a flux of charged particles and under certain conditions, particles with energies measured in keV can differentially charge spacecraft surfaces to potentials which cause arcing and possible damage (Ref. 1). Even if all conductive surfaces are interconnected, potential differences can exist between conductors and the surfaces of charged insulators. The sudden discharge of dielectric surfaces to nearby conductors is to be avoided by designing the interface between dielectric and conductor such that a stable charge distribution is maintained near the interface.

This project has been concerned with the measurement of interface characteristics such that design criteria could be developed. The work has dealt exclusively with metal-backed thin dielectric films, primarily of flourinated ethylene propylene (FEP Teflon) but also of polyimide (Kapton). More specifically the investigations have consisted of the following:

a) Measuring dielectric surface charges (surface potentials) in the vicinity of various types of interfaces formed with conductive aperture plates, conductive divider strips, and slits in the film.

b) Seeking correlations between charge distribution and the probability of a flashover or sudden discharge.

c) Identifying causes of flashover.

d) Determining physical processes which maintain the observed charge distributions.

It was expected from the beginning of the project that a correlation would be found between the charge-density gradient and the probability of a flashover. However, the observations do not support such a conclusion. The causes of flashover have been identified in most cases as being microscopic flaws in the interfaces, and no flashovers have been observed which cannot be attributed to small flaws. Now it may be true that the causes can still be explained in terms of gradients, but the details are too small to be resolved with the techniques we have used. Even though the correlation did not develop as we expected, we were still able to design interfaces which were highly immune to the occurrence of flashovers. Also, the studies of gradients led to some informative measurements of the secondary emission coefficient as it depends upon electric field.

This study of interfaces is not alone in that numerous other people have been concerned with the characteristics of dielectrics in vacuum systems. Ongoing work at NASA-Lewis Research Center, typified by the report of Stevens, Berkopec, and Blech (Ref. 2), is concerned with the testing of dielectric materials under simulated space conditions. Balmain (Ref. 3) has induced discharges between adjacent regions of a dielectric surface by irradiating specimens in an electron microscope. A general review of solid insulators in vacuum is given by Hawley (Ref. 4) who emphasizes failures along a dielectric surface which bridges two electrodes. De Tourreil and Shivastava (Ref. 5) discuss charging mechanisms for dielectric surfaces which bridge electrodes.

Those aspects of this work related to the effect of electric field on secondary emission are to be discussed in a companion report (Ref. 6) now in preparation. Two progress reports (Ref. 7,8) were issued under this project and a paper presented at the Spacecraft Charging Technology Conference of 1976 will appear in the conference proceedings (Ref. 9).

Apparatus and test equipment were fairly conventional and details are discussed in the section following this one. Next, an explanation is given of the techniques for measuring surface charges. The methods of inferring surface potentials from surface charges are then presented along with beam probe methods which give direct measurements of surface potential. Data collected by the various methods are given at this point. The latter sections of the report describe the occurrence and causes of flashover with the presentations being divided into two parts, one for specimens without punctures or slits and the other for specimens having these features. The concluding section presents a summary of major findings and a set of recommended design practices.

APPARATUS AND TEST EQUIPMENT

Throughout the course of the grant, the same vacuum system, power supplies, and instruments were assigned to the work. However, with numerous minor modifications we adapted this basic equipment to our changing techniques of measurement. This chapter, without explaining the measurements themselves, describes the equipment and instrumentation which have evolved.

Vacuum System

All vacuum measurements were made in a 45-cm stainless steel bell jar which was evacuated by a turbomolecular pump. The base pressure when the system was clean was 10^{-6} Torr, though as the project progressed and ever increasing amounts of hardware were added to the chamber, the base pressure rose to 10^{-5} Torr. A legitimate concern is the effect of pressure upon the phenomena being investigated and thus further comments are in order.

The pressure in the region of geosynchronous orbit is low compared with that of space simulation chambers. A critical difference is that, in chambers, a monolayer of atoms will exist on surfaces whereas in space, the layer may form slowly if at all. As long as our work is constrained to surfaces with monolayers we must acknowledge the possibility that results will be different in the space environment; we can only ascertain whether or not pressure variations in the monolayer regime have any effect.

Experimentally, we find little dependence of measured data upon pressure unless we raise the pressure to the neighborhood of 10^{-3} Torr. At this high of a pressure, dielectric surfaces lose charge in a period of a few seconds..

Certain measurements drift significantly for about two days after a new specimen is placed in vacuum. The existence of impurities is the expected cause since no cleaning of specimens was done, though they were prepared without finger contact. In certain cases the specimens were exposed to a heat lamp which cured epoxy bonds and may have expelled some contaminants having low vapor pressure.

Electron Source

The source, which was described previously (Ref. 10), produced a diffuse beam of electrons that arrived at the specimen target plane. The beam diameter at half maximum was 7 cm. Electrons were nearly monoenergetic since they were emitted from a heated tungsten filament which was negatively biased. The accelerating power supply produced a 1% ripple and voltage was monitored with a divider and meter calibrated to an accuracy of 1%.

Recent work has required the measurement of changes of beam voltage, these changes being as small as 0.5%. Because the 1% meter circuit was inadequate, a separate differential measuring circuit was installed as shown in Fig. 1. Once the main supply voltage had been set at the desired value, the reference voltage was adjusted until meter V_2, having a range from 0-2400V, indicated zero. Then small changes in the accelerating potential were read directly from V_2. This meter required electrostatic shielding to function properly and a spark gap protected it against over voltage.

A switch was built into the filament heating circuit so that the electron beam could be turned on or off abruptly. However, this feature was impractical because the filament had a thermal time lag. Later a mechanical shutter was installed and the filament switch was used very little.

Baffles and Shutters

Inside the vacuum chamber were found not only the electron source and the target but also numerous baffles and shutters which limited the exposure of the target to the beam. In Fig. 2 are shown these auxiliary pieces of hardware which prevented electrons from reaching the underside of the specimen and allowed for complete or partial irradiation of the upperside of the specimen. Not shown are electron collectors which monitored secondary emission since this function is described in a separate report (Ref. 11).

All specimens were mounted on 20 cm discs of aluminum in the position shown in Fig. 2. Since the specimen leads carried small currents at low voltages, they were susceptible to electrical interference and particularly to stray electrons that might impact upon them. This is why the set of three baffles was placed around the mounting disc.

The specimen leads exited from the vacuum chamber through a 9-pin feedthrough designed to have long leakage paths between pins, and furthermore, the signals were always less than 10 volts in magnitude. Thus, leakage between pins was negligible.

The large grounded baffle shown in Fig. 2 divided the bell jar into two parts connected only by an orifice through which the electron beam would pass. The orifice could be completely closed with the movable shutter above the baffle or it could be reduced to a 2.6-mm diameter port by using the shutter below. Note the turned edge on the lower shutter which is to reduce scattering and note the placement of the tube which collimates the beam. The need to reproducibly direct the small beam at various parts of the specimen required that the lower shutter be equipped with a pointer and scale.

Electrometers

Two battery-operated instruments were configured for measuring charge or current as needs demanded. They produced proportional analog signals which were recorded directly on a dual-channel strip chart. Bandwidth for current measurements varied with the choice of scale settings and was determined primarily by the capacitance and resistance of the input circuit. Though the meters built into the electrometers for viewing were relatively slow, the strip-chart recorder had a fullscale bandwidth of 50 Hz. The optimum instrument time constant in any given instance depended upon signal bandwidth and noise level.

MEASURING SURFACE CHARGES

Because this project has dealt exclusively with thin dielectric films, surface charges could be measured from the back sides of the specimens without perturbing the fields near the surfaces being investigated. All of the dielectric specimens were coated on the back side with metal films which were held at ground potential. Charges adhering to the exposed surface of a specimen would induce a like amount of opposite charge on the metal film. This induced charge could be measured with an electrometer while the metal film was held at a virtual ground potential.

Segments

It was desired, of course, to measure the charge distributions on a specimen. Thus, a measure of charge induced on a continuous metal film was insufficient. This problem was overcome by cutting lines in the film so as to produce isolated metal segments, each of which was held at ground. Then charges induced on each segment were measured and identified with the surface charge directly opposite that segment. Fig. 3 illustrates how an electrometer was connected to measure the charge on a specific segment. The electrometer was used in a feedback mode which maintained the segment at virtual ground potential.

Several segments, usually arranged in a ladder formation, were cut into a given specimen. The pattern shown in Fig. 4 is typical where the segment width is approximately 1.5 mm and the length is somewhat greater. The narrower the segments, the greater was the resolution in the measurement of charge distribution. However, if the segments were to narrow, electrical connections to the segments were unreliable. These connections, made with a drop of silver-laden epoxy and #32 copper wire, would break easily if the contact area between the drop and the film was too small. This was because of poor adhesion of the epoxy to the metal films. Except for a few cases the metal film was a double layer of silver and inconel, the latter being exposed. The use of other metals or other bonding techniques might allow the use of smaller segments so that greater resolution could be attained.

The segments themselves were cut into the metal film by an electrical discharge as shown in Fig. 5. The film was charged so that the specimen would be electrostatically attracted to the grounded work bed. Then a grounded metal point near the film's surface would attract a spark which would vaporize a small amount of the metal film. The R-C combination in the power supply circuit caused the system to behave as a relaxation oscillator and to produce a repetitive spark. Lines were etched in the film by moving the point parallel to the surface at approximately 1 cm/sec.

Charging and Discharging of Surfaces

The electron beam deposited charges on the specimen and the response of the electrometers-strip-chart recorder combination was sufficiently fast to provide detailed records of the charging phenomena, even with highest current beams attainable. The time required for a surface to reach a steady state charge was reduced by increasing the beam current density. However, the final amount of charge on the surface depended only upon the beam voltage and not upon the current density. (A few measurements at a density as high as 10 $\mu A/cm^2$ showed a steady state charge about 10% less than the usual value.) Though one could establish patterns of charge on a surface by using a narrow beam, this technique was not used.

Discharging the surface was more complicated than charging it because assurance of a complete discharge was needed. One method that was slow was to raise the system pressure with a controlled leak to 10^{-3} Torr and wait approximately one minute. A much faster method was to remove charge from the surface by secondary emission, though certain precautions were needed for this method. A third method, the generation of ions, was not used though occasionally, a slow discharging did occur because of ions created by electron bombardment of background gas in the chamber.

The use of secondary emission was possible because for certain energy ranges of electrons striking the specimen, the secondary emission coefficient exceeded unity and the surface lost charge. In practice, the beam voltage was gradually reduced to zero and the surface voltage fell with it. However, if the beam current density was too low, the process was tedius and one could easily reduce the beam voltage too rapidly, leaving charge on the surface of the specimen. Current densities exceeding 100 nA/cm^2 were convenient for discharging of specimens.

Reliability

The charge measurements were not repeatable within the capabilities of the instruments themselves. The reasons can generally be classified as drifting and hysteresis. Some segment measurements were more reproducible than others.

Various causes of drifting could be identified. First of all, electrons scattered from the beam could reach the back side of the specimen and produce a drift in the electrometer. Shielding virtually eliminated this problem. On the other hand, a drift caused by current conducted through the specimen could not be eliminated. For 5-mil FEP Teflon, this drift was not important though for 2-mil stock and for Kapton, the effect necessitated the correction of data. At one time dirt on contacts outside the vacuum created some problems, though they were easily remedied. Drift, though a nuisance, could be controlled or corrected.

A more serious problem than drift was hysteresis associated with the charging and discharging of specimens. Some segments were much more susceptible to this problem than others and a detailed investigation was conducted for one of them. The nature of the hysteresis is illustrated in Fig. 6 which records several readings of an electrometer taken in rapid succession such that drifting was inconsequential. In fact the slow drifting of readings with a constant beam voltage of 10 kV was in the negative direction. Applying a bias voltage to the segment would influence the hysteresis effect, a negative bias increasing the hysteresis. Then it was discovered that after the application of a bias of -100V for several minutes (no beam during that period) that there was no hysteresis when the system was operated with zero bias. However, the cure was not permanent and data taken for the segment was generally unreliable. The hysteresis was inherent in the specimen itself and it was influenced by the application of bias voltage to the segment. Why some segments show this phenomenum is not known though our speculation is that it is related to contamination on the back side of the specimen.

DETERMINING SURFACE POTENTIALS

The measuring of surface charges as described in the previous chapter is preliminary to the calculation of surface potentials. A knowledge of the capacitance of that portion of dielectric film adjacent to a segment allows the calculation of the potential on the surface when charge has been measured. However, an entirely different technique measures surface potential directly and reinforces the results obtained from the charge-capacitance method. The idea is that a charged surface will abruptly lose some charge when it is struck by a probing beam of electrons that has an energy slightly greater than the surface potential.

The two techniques for finding surface potential complement each other. The method based upon segment charges and capacitances provides the better spacial resolution while the beam probe provides more reliable voltage data. Results obtained with both techniques and several of their variations are presented in this chapter.

Segment Capacitances

Values for segment capacitances may be obtained in different ways which do not necessarily yield consistent results. Voltage non-linearity can account for some discrepancies, yet even linear results depend on tolerances of the measured parameters.

A simple method of obtaining capacitances is to enlarge a photograph of the segments and to measure areas. Then from the flat-plate approximation given by $C = \varepsilon_r \varepsilon_o A/d$, the capacitance is found. This method requires a knowledge of film thickness d and relative dielectric constant ε_r. All of the factors have associated tolerances but the ratio ε_r/d should vary little with the choice of segment on a given specimen. Areas are hard to estimate because of the uncertainty associated with fringing fields between neighboring segments. In one exercise on FEP Teflon, the average of nine segment capacitances was found to be within 1% of the average found by the water-drop method (discussed next) though one segment showed a discrepancy between the methods as high as 11%. Nominal values of $\varepsilon_r = 2.1$ and $d = 5$ mils were used.

The water drop method of measuring capacitance was highly reproducible and generally favored, though it was restricted to low voltages. With the vacuum system open, a drop of a weak aqueous salt solution was placed on the surface of the specimen so that it completely overlapped the boundaries of the segment being measured. While charge induced in the segment was being monitored, an electrode in the drop was raised to potentials of 500 V and 1000 V. Within this range the capacitance was linear. The method of measurement contaminated the specimen and it was usually restricted to low voltages because of arcing which would otherwise occur between the water drop and nearby grounds. In one series of tests at higher voltage, specimen capacitances increased about 5% as voltage was raised to 4 kV.

Segment capacitances could be measured in vacuum at any desired voltage when the surface potential could be measured with the beam probe technique. Induced charge was monitored in the usual way. However, this method was limited because of the ineffectiveness of the beam probe near interfaces. When the interface could be temporarily removed, this technique was very useful.

Surface Potentials From Charge-Capacitance Data

One of the objectives of this project was to measure surface potentials in the vicinity of interfaces between dielectric and metal. All of the specimens had boundaries or interfaces defined by placing an aperture plate over the specimen and some of them had additional interfaces as well.

The aperture plates which defined the outer boundaries of the specimens, were fabricated of aluminum sheets from 1.2 to 1.5 mm thick. Apertures were milled such that the sides of the cut were perpendicular to the face of the aperture. Then sharp edges were smoothed lightly. The aperture plate was held against the face of the specimen with screws which passed through the aluminum mounting plate.

One of the earliest and most detailed surface potential maps is shown in Fig. 7, it being taken for that 5-mil FEP Teflon specimen shown in Fig. 4. The data points are based on charge measurements and water-drop capacitance measurements. Our later work with beam probes shows that all data points are slightly low as, for example, the peak potential in a 20 keV beam should be approximately 18.5 kV. Nevertheless, the trends are well defined. Practically no perturbation is seen beyond that point which is 10 mm from the edge of the aperture. (The perturbation extends less distance for lower beam voltages.) Though the perturbation extends up to 10 mm, the surface potential is depressed relatively little in regions beyond 3 mm and the depression to 50% of the normal level occurs only within 1 mm of the aperture edge. From the slope of the lines near the aperture edge, one can estimate the surface field strength to be approximatley 15 kV/mm.

Methods similar to those of the preceding example were used to map the potential on the surface of Kapton and results are shown in Fig. 8. Very similar results are found though the accuracy of the measurements is not as good. For example, several points indicate surface potentials in excess of beam accelerating voltage and the points at 8.8 mm are inconsistent with the others.

The two preceding series of measurements were for 26-mm circular apertures on 5-mil stock but results did not depend on aperture diameter as shown by a series of measurements for a 50 mm aperture. Also a similar distribution was attained near the edge of a 26 mm square aperture. Edge effects seem unaffected by specimen size as long as the edge regions do not overlap. As for aperture plate thickness, results described later in this chapter for a 0.076-mm aperture plate qualitatively suggest the occurrence of a potential gradient similar to those for thicker aperture plates. The thickness of the specimen is felt to be of little importance because, as will be argued later, the potential gradient is closely connected with the surface phenomena of secondary emission.

A very different type of interface, a slit, was examined next. As before, the specimen area was defined by a 26 mm aperture plate but in this case a 10 mm slit was cut along a diameter of the 5-mil FEP Teflon specimen. Rather than leave the edges of the slit loose, we backed the specimen with a stainless steel strip and anchored both slit edges to the backing with silver-laden epoxy. Surface potential near the slit was less depressed than it was near aperture boundaries. Fig. 9 illustrates the difference between the two type of data. Note that the figure labels are for the specimen having a slit. The curves for the case without a slit are drawn as if the aperture edge were at the location labeled "slit". Potential measurements near the slit could not be made for beam voltages above 10 kV because flashovers were frequent. If we can say that the surface potential is zero at the slit where silver-laden epoxy is exposed, then the gradient near the slit may be substantially higher than the value of 15 kV/mm which was found near the aperture edge.

The extent of interaction between two adjacent dielectric systems can influence design criteria and thus a set of apertures was designed to provide a measure of the interaction. Rectangular apertures of 19 x 25 mm were cut into two plates as shown in Fig. 10 so that the apertures could be joined to form one larger rectangle. Then various dividing strips were clamped between the two plates to control the interaction between the two exposed dielectric surfaces. The half-round divider was chosen because the shape was compatible with a computerized calculation of electric potentials described elsewhere (Ref. 12). Segment capacitances were measured for this system by removing the divider, charging the segments with a 20 keV beam to a surface potential of 18.5 kV, and measuring the charge induced. Then with the divider in place, the segments charged to less than 18.5, the actual voltage being assumed less in proportion to the induced charge. Results for a 2.36 mm diameter half-round, which was the smallest of the dividers used, are shown in Fig. 11. Voltage distribution near the half-round differs little from that near the aperture edge. Unexplainedly, one data point (not in the figure) showed a surface potential exceeding 20kV.

Charge Release Mechanisms

Near dielectric-metal interfaces, the steady state surface potential is less than it is elsewehre. Even though these regions of depressed potential are struck by energetic electrons, they do not accumulate as much charge as predicted by an analysis of secondary emission which uses conventional data. Thus, some charge release mechanism is active in these regions and it is to be identified.

Our conclusion is that the secondary emission curve, illustrated in Fig 12 (Ref. 13) is modified by the presence of strong electric fields near the interfaces. A detailed analysis of this effect is presented in a companion report (Ref. 14). However, some discussion of alternative mechanisms is included here.

If secondary emission is the active release mechanism, the surface will charge to a potential such that primaries arriving at the surface are balanced by an equal number of secondaries leaving. Thus, the surface potential is less than the accelerating potential by the number V_{crit} which corresponds to an emission coefficient of unity. However, if other charge-release mechanisms are active, the surface potential will be lower yet.

A key observation is that surface potential does not depend upon beam-current density. Thus, the primary flux must be balanced by an equal charge release and whatever charge release mechanism is active must be proportional to primary flux. Two mechanisms could possibly meet this criterion, one is secondary emission and the other is emission caused by X-ray bombardment since electron flux to the aperture plate will produce X-rays in proportion to flux density.

A test for effects of X-rays gave negative results. If X-rays were important, then a change in material of the aperture plate would supposedly change the spectrum of X-rays and thus change the charge distribution near the edge of the aperture. The usual aluminum aperture was replaced with one made of copper because copper has its K-edge conveniently at 8.99 kV. Then charge density measurements were made for electron beam energies in the neighborhood of the K-edge, both above and below. Results were no different from those obtained with aluminum (K-edge at 1.5 kV) and thus the effect of X-rays is considered to be unimportant.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

Conductivity of specimens in a quiescent state cannot account for the charge losses near the interfaces because it is not proportional to flux. However, primary bombardment might produce a conductivity proportional to dose rate raised to some empirically determined power (Ref. 15). We conducted a series of tests on 2-mil FEP Teflon that showed a strong dependence of bulk leakage current on surface potential when the sample was being irradiated. In these tests increasing potential from 15 to 20 kV caused an increase by a factor of 10 in current leaking to the backside coating. When we consider that conduction can depend upon bulk field strength, surface field strength, contamination levels, and primary beam intensity, we feel that conductivity cannot be expected to provide a charge loss mechanism proportional to beam intensity. However, the previously mentioned droop of surface charge density under high current conditions may be related to an enhanced conductivity.

Transient Surface Voltages

Data in the previous section represent steady state conditions but the electrometer signals varied with time and transient data could also be obtained. One transient of primary interest, the flashover, will be described in later sections. Another transient phenomenum, which we have seen frequently, is illustrated in Fig 13. Charge vs. time is shown for two segments, one near the edge of the aperture and one in the middle of the specimen. With no initial surface charge, the beam voltage is raised quickly from zero to some fixed value and charges are deposited. The segment near the edge overcharges and then relaxes to its steady state condition.

Electron Beam Probe

Measuring surface potential with an electron beam requires that a person be able to determine whether or not the beam strikes the surface.

If the beam energy is too low, the surface is not touched by the beam. Thus the potential of the surface is equal to the maximum beam accelerating potential for which the beam does not touch. Electrometers connected to the backside sense whether or not the beam reaches the surface.

In practice we have charged the surface to a steady state and interrupted the charging beam with the upper shutter shown in Fig. 2. Then the lower shutter is positioned to admit a narrow beam at the desired location and the electron accelerating voltage is lowered to the desired probing value. While the electrometer is sensing the charge, the upper shutter is opened to allow the beam to approach the specimen surface and note is made of whether or not an interaction occurs. The process is repeated for different probing voltages as necessary to determine the surface potential at that location.

The response to a probing beam is explained in terms of the secondary emission curve illustrated in Fig. 12. The primary impact energy is the excess of the beam energy (keV) above the surface potential (kV) and it is usually such that the secondary emission coefficient exceeds unity. Thus, the response to a beam probe is a loss of electrons from the specimen. There is, theoretically, a small range of beam energies where a gain would be possible. However, responses of this type have not been seen. Our metering system has a voltage resolution of 20 V which is smaller than the range over which a gain might occur. However, the ripple of our power supply probably obscures this response. In practice we monitor responses at 100 V intervals and assign the highest value having no response to be the surface potential.

Though the measurement is described above in terms of surface charge, much greater sensitivity is attained by measuring current to the surface (as indicated by an electrometer connected to the back side). A beam interaction is thus identified by an abrupt change (generally positive) in the electrometer current. Typical responses to the 2.6-mm diameter probing beam are shown in Fig. 14. It should be noted that if the probing beam voltage exceeds the charging beam voltage, then the surface will accumulate electrons and the current pulse will have the opposite polarity to those shown in the figure.

One source of error in the method is that surface potentials may change between the times that the charging beam is interrupted and the probing beam is activated. More will be said about this in the next section. Conceivably, one could eliminate this problem by probing with a second beam source while the charging source is in operation.

Probing With a Small-Diameter Beam

Measurements of potential may be made without using segments if the beam can be directed toward the desired spot. However, near the edges of a specimen, strong fields deflect the beam away from its intended target area and the actual target area remains undetermined. Conceivably, one could use a small beam with segments such that one could tell where the beam strikes. However, in our work we did not use small beams except in regions of uniform surface potential. Away from the aperture edges, the surface potentials on FEP Teflon were uniform to within 100 V.

We made measurements of surface potential at the center of circular apertures for various conditions. Measurements of secondary electron coefficient, made by an extension of this method, and surface potential as functions of electric field strength on the surface are described elsewhere (Ref. 16). However, work reported here is for specimens with a relatively low surface field strength, that associated with the surface charge itself.

Surface potential is affected by aging of specimens, or more precisely, time in vacuum. One 2-mil FEP Teflon specimen had a measured surface potential of 12.6 kV in a 15 kV beam the first day in vacuum. The next day the potential was 13.2 kV and the next, 13.4 kV. Another 5-mil specimen was measured at 7.9 in a 10 kV beam and the next day at 8.3 kV.

The low voltages measured on new specimens can be attributed to decay during the period when the beam is being reconfigured. Decay rates can be measured by setting the probing beam voltage at some level known to be too low and waiting. A response occurs when the surface potential has decayed to the level of the beam accelerating voltage. Data of this type are shown in Fig. 15 for a 2-mil FEP Teflon specimen charged in a 20 kV beam. One can extrapolate to zero delay and ascertain the surface potential at that moment when the charging beam is interrupted.

Probing With a Diffuse Beam

Although the simultaneous use of a small probing beam and segments is very tedious, one can use a diffuse beam with segments. Voltage resolution comes from the beam source and spacial resolution from the segments. Relatively little work was done with this method and results found were inconsistent with other results. One problem was that the responses measured on the various segments did not vary with beam voltage as expected. Responses were seen, for example, for beam voltages known to be well below surface potentials. Where data points could be obtained, they showed a much smaller depression of surface potentials near interfaces than was shown by the charge-capacitor method.

FLASHOVERS TO APERTURE PLATES

The flashover is an event whereby charge on the surface of a specimen is suddenly released and then collected by one of various grounded metal surfaces. The occurrence of a light flash and the erosion of dielectric are signs that numerous ions are released. The process is rapid, unresolvable with our equipment, and it can be resolved only on a nanosecond time scale (Ref. 17).

In this chapter, flashover is considered only for the specimens which have an unbroken dielectric film. Thus the charge collection must be by an electrode placed on or above the exposed surface. This type of system differs greatly from systems which have holes or slits, these being discussed in the succeeding chapter.

Single Apertures

Much work has been done with circular and sometimes rectangular apertures cut into an effectively infinite ground plane. Though the circular apertures were cut from solid plates, the rectangular apertures were formed by butting two pieces of aperture plate together. In one case the joint appeared to be a cause of frequent flashovers, though otherwise there was little difference in the types of aperture. Ignoring, for now, the problem of joints, we present the general characteristics of specimens exposed though an aperture.

The most important point to be made is that these specimens had very low flashover rates when compared with specimens having slits or holes. Furthermore, the rates decreased as the specimens aged. The reciprocal of rates, mean times between flashovers, for one specimen are shown in Fig. 16 yet it should be noted that these points were taken immediately after the specimen had been exposed to air. One specimen was exposed to a 21 kV, 3 $\mu A/cm^2$ beam for 20 minutes without experiencing a single flashover. Recording of surface charge data could proceed for a period of several days with no flashovers occurring.

During these tests, steady state conditions were attained on the specimen surfaces in a few seconds, yet often minutes would occur between flashovers. Thus steady state conditions prevailed during most of the exposure time. However, flashovers would often occur in bunches. One run, for example, registered 22 flashovers in 20 minutes, and six of those occurred in rapid succession with intervals of about 1 second between them. Numerous similar examples indicated that the probability of flashover is highest when a specimen is recovering from a previous flashover.

Flashovers, when they occur, are usually complete, that is, the entire specimen is completely discharged. However, small perturbations of segment charges do occur. These represent losses of perhaps five percent of the charge and they are not necessarily seen on both segments being monitored.

Rarely, partial discharges will occur where the segments being monitored lose substantial fractions of their charges. An exceptional case was found, however, where partial discharges were common. This specimen was of 5-mil FEP Teflon but with an aperture plate fabricated from 0.076-mm stainless steel shimstock. In Fig. 17 are shown two time histories of specimen charging events with two segments being monitored in each case. Segment 5 was at the center of the specimen, segment 3 touched the edge, and segment 9 was in an intermediate position. Though the figure illustrates events having several partial flashovers, a single flashover was commonly observed during a charging event. The specimen had a low flashover probability once the steady state condition was attained.

Specimens which had long exposures to the electron beam were coated near the edges, presumably because of flashovers. A microphotograph showing this condition is reproduced in Fig. 18. The non-conductive, whiteish deposit is thought to be aluminum which is oxidized on exposure to air. The coating was not uniformly deposited but it consisted of many thick, irregular patches which were superimposed on a uniform background. The patches were widest next to the aperture plate and it is possible that a patch can be identified with one or a few flashovers to that part of the aperture plate.

As is evident in the following discussions, the cause of flashovers to aperture plates is not linked to the charge density gradient on the dielectric surface. Rather, it is likely that the cause is a particle of dust or an irregularity in the aperture plate surface. This is reasonable because a flashover will dislodge an imperfection and thus reduce the probability of further flashovers.

Double Apertures

The two-aperture system previously described and shown in Fig. 10 was designed so that interaction between the two dielectric surfaces could be monitored. The charge distribution near the dividing strip was little different from that near the outer edge, yet for this system, flashovers were more frequent. The fact that flashovers were more frequent would seem to be attributable to the existence of the two adjacent segments and some type of interaction, but when one side was covered with a foil, the other side continued its pattern of flashovers without change. Thus, an explanation of the higher rate was sought elsewhere.

The higher flashover rate was seen on only one side and not the other; furthermore, flashovers were generally accompanied by a concentrated flash of light at one corner where a joint occurred between the divider strip and the aperture plate. Though visual examination of the joint provided no conclusive evidence, it was felt that small gaps or ill-fitting pieces were possible causes of the frequent flashovers. The rate was reduced by reassembling the system and aging it. Since the corners without joints were not observed to have bright flashes, we conclude that corners themselves are not bad. However, some joints will apparently precipitate flashovers.

If a person attempts to reduce the severity of a flashover on an extended dielectric surface by breaking that surface into smaller pieces separated by dividing strips, then he needs information as to how wide the strips must be if a flashover on one piece is not to spread to another. For our smallest divider, which had a diameter of 2.36 mm, we observed 40 flashovers in a 20 kV beam. During the 14 minute run, 32 flashovers occurred on side A only, three occured on side B only, and five occurred simultaneously on both sides. The five were assumed to be flashovers that were initiated on one side and which spread to the other. At 22 kV, we observed 46 on side A, four on side B, and four which were simultaneous on both sides. Also, six partial flashovers occurred. Our next largest divider, having a diameter of 4.8 mm, was inserted and in a 20 kV beam we saw 49 flashovers on side A, one on side B, and none which were simultaneous on both sides. Larger divider strips were not tested as the 4.8 mm strip provided good isolation.

Fine Wires

Though these various systems described in this chapter have low flashover rates, it is possible to have very high rates by placing fine wires or meshes on the surface of the dielectric. In one demonstration a grounded 10-mil stainless steel wire was layed along the surface of FEP Teflon and the specimen was exposed to a 20 kV beam. Steady state charge distributions were never attained as flashovers occurred during the charging transients. Light flashes were concentrated on the wire.

FLASHOVERS TO HOLES AND SLITS

Unbroken dielectric films are preferred to those which expose the underlying ground plane but imperfections may occur for various reasons. Holes may be formed by mechanical puncturing or by dielectric breakdown at high voltage. Also, some dielectrics are installed as tapes whose edges are exposed and perhaps butted together. Thus, the effects of holes and slits on flashover rates are of interest.

Making Holes and Slits

We tried to produce holes by applying an electric field across 2-mil FEP Teflon specimens backed with stainless steel. Silver-laden epoxy bonded the metal coating to the stainless steel. With a 20 kV drop across the film, a leakage current of 3 nA/cm^2 was detected but there were no catastrophic failures. Values of breakdown field strength measured by various workers have varied over a range of 10 to 1 (Ref. 18) and for our particular geometry, values appear to be high. Since we could not make holes electrically we made them by pressing the point of a draftsman's divider against the surface.

Slits were cut with a sharp knife blade though two different procedures were used. In one case the slit was cut before the epoxy and backing were applied. In the other case, the backing was applied first and then the slit was cut. When the cut was made first, the flashover rate was high from the moment the beam was turned on and it remained more or less constant. When the fabrication procedure was revised, however, the rate was initially low and it gradually increased to become like the first case.

The Slit Specimens

Extensive flashover-rate data were obtained for a 5-mil specimen which was slit before the backing plate was attached. The results, summarized in Fig. 19, show that the rate increases with beam current density. These trends have been found in all of our work. It may be said that for the higher rates, steady state conditions were never attained and the flashovers occurred during the charging intervals. Flashes of light were concentrated in the vicinity of the slit when flashovers occurred. Post-examination of the slit revealed that epoxy had flowed upward through the slit to leave a protruding bead as shown in Fig. 20. This bead is somewhat similar to a fine wire and is considered to be the cause of the flashovers.

When a slit is cut after the backing plate is applied, the bead does not form, and indeed, such slits did not induce flashovers at first. Observations were made with both 2 and 5-mil specimens. We had to excite the specimen with a 22-kV beam at 100 nA/cm^2 to cause a few flashovers and from that point on the specimens deteriorated, eventually demonstrating frequent flashovers at 15 kV and 40 nA/cm^2. Resting specimens would reduce their tendency to flash, though they never recovered their initial state.

The probability of flashover was high when a specimen was recharging after a preceding flashover. This was well demonstrated by the 2-mil specimen which developed a pattern of repetitive flashovers at 15 kV with a steady state not being attained between events. The level at which flashover occurred varied little from event to event. However, the string was broken by reducing the beam voltage to 12 kV. Then the voltage was raised to 20 kV over a period of several minutes with only one flashover occurring.

Both the 2-mil and 5-mil specimens showed burn spots along their slits after having experienced numerous flashovers. These spots are the cumulative effect of many flashovers and since the probability of flashover increases with the number of flashovers, we conclude that the burned spots are the trigger points for the flashovers. Some spots for the 2-mil specimen are shown in Fig. 21.

Visual observations of the 5-mil specimen reinforced the concept of a trigger point. Flashovers were initially accompanied by one spot of light on the slit, always in the same place. As time went on, two other spots appeared on the slit and a spot of light also appeared on a nearby pinhole. Near the end of the observations all four spots were illuminated simultaneously by each flashover. Several burn spots developed along the slit and at the pinhole.

Slits in themselves do not induce flashovers; the cause is associated with enlarged holes or protruding epoxy. However, even carefully made slits are undesirable because their probability of flashover increases with the occurrence of flashovers.

Pinholes

Specimens with pinholes were unlikely to flash when the pinholes were newly made. None having only pinholes were aged to the point where flashovers would become frequent, but as noted above, specimens with both holes and slits showed simultaneous light flashes and burns on the holes as well as at points along the slits.

Exposed Edges

One experiment was planned so that a portion of the aperture plate could be moved and that the edge of the dielectric sheet could thus be exposed. This sheet rested upon an underlying aluminum ground plane but it was not bonded to the plane. Even with an exposed edge, the flashover rate was low as long as the aperture plate left a gap no larger than 0.5 mm. Flashover rates increased as the aperture plate was drawn further away from the edge of the specimen.

CONCLUSIONS AND RECOMMENDATIONS

Dielectric surface potentials can be measured by a variety of methods, some more reliable than others, and data have been collected near several dielectric-metal interfaces.

The distribution is not a very sensitive function of the interface design and, contrary to original speculation, the distribution is not related to the probability of flashover. Microscopic irregularities in the interfaces are responsible for initiating flashovers and these can be largely eliminated by using proper design techniques.

Techniques for Measuring Surface Potentials

Several techniques were used, some more successfully than others, for measuring surface potentials. These techniques divide into two classifications, the charge-capacitance methods and the probing-beam methods.

Considering the dielectric film to be equivalent to a capacitor, we measured the capacitance of defined regions of the film and measured charge stored on the surface of the film. The ratio yielded surface potential. Charges were measured by electrometers attached to various segments of the metallic coating on the back side of the film. On the other hand, capacitances were measured by several methods including the scaling of areas from enlarged photographs, the direct measurement of charge with a water drop forming an electrode on the exposed film surface, and the measurement of charge with an electron beam establishing a reference voltage on the exposed surface. The different methods were subject to several sources of error such that the data points showed significant scatter, though these methods provided better spacial resolution than the probing-beam methods. The minimum segment dimension was 1.5 mm though the use of other fabrication techniques might allow use of smaller

The surface potential can also be found by determining the highest electron beam energy for which electrons do not strike the surface. In particular, the specimen is abruptly exposed to a probing beam of a certain energy and note is made as to whether or not a current is induced induced in the specimen's substate. If so, the beam did strike the surface and the process is repeated for a lower beam energy. If not, a higher beam of energy is used. The process is continued until the desired resolution of energy is attained

Beam measurements are more accurate in the center of the sample than charge-capacitance measurements although they provide less spacial resolution. Near specimen boundaries, beams are deflected by local fields such that the impact points are not well defined. The simultaneous use of beams and segments might provide both spacial resolution and accuracy of potential measurements but the details of this type of method were not developed.

Potential Distribution Near Interfaces

For a metal-backed dielectric film covered with a conductive aperture plate and exposed to a monoenergetic beam of electrons, the surface charge density will be less near the edge of the aperture than on central portions of the film. Away from the aperture edge, the surface charge is such that the potential is less than the beam accelerating potential by the amount of the secondary emission critical voltage. Certain specific conclusions are as follows:

a) For the 5-mil FEP Teflon and Kapton specimens investigated, the perturbing effect extended about 10 mm away from the edge of the aperture in a 20 kv beam, and lesser distances for lesser voltages. The perturbation was relatively small except within 2 or 3 mm of the edge where the surface charge density was substantially below the unperturbed value. Surface field intensity is as high as 15 kV/mm adjacent to the aperture plate.

b) The perturbation did not depend upon beam current density, material of the aperture plate, or pressure attained by the vacuum pumps.

c) Though complete data are not available as justification, we feel from qualitative observations that the perturbation in charge density does not depend strongly on aperture plate thickness or dielectric film thickness.

d) The perturbation does not depend on the size of the aperture as long as the diameter exceeds a minimum value of twice the perturbation length.

Near a slit in the dielectric film, the surface charge density is less than the unperturbed value, though the perturbation does not extend as far from the slit as the perturbation extends from the aperture edge. Because the slit was backed by a strip of stainless steel, measurements could not be made as close to the slit as to the aperture edge, and thus the region of large perturbations could not be mapped. Though surface fields cannot be estimated accurately in this case, they are likely to be several times larger than near the aperture edge.

If a specimen surface is divided by a grounded metal barrier strip having a width of a few millimeters or more, then the surface charge distribution near the barrier is the same as it is near the edge of the aperture plate.

Causes of Flashover

One objective of this work was to relate flashover probability to the distribution of charge near an interface. However, the probability is found to depend on factors other than charge distribution. Alternatively, it may be said that the probability of flashover depends upon structual details too

Evidence shows a steeper charge-density gradient near a slit than near an aperture edge. Yet the slit is not necessarily a cause of flashover. Newly cut slits would have little effect on flashover rates, but the slits would age, showing microscopic changes, until rates became high. The slit which was filled with a microscopic bead of epoxy had a high probability of flashover. The system with a barrier strip had gradients like those near aperture edges, yet it showed a higher probability of flashover than normal for this type of gradient. The cause of flashover was attributed to be a joint in the aperture structure. Fine wires on the surface of the specimen caused a high rate of flashover. For simple aperture plates, flashovers were infrequent yet presumably linked with dirt or imperfections in the machining of the plate.

Reviewing the causes of flashover reveals that in every case, the cause could be linked with small irregularities in the interfaces. These irregularities were generally much smaller than the 1.5 mm resolution attained in charge measurements, and in fact, many details of these irregularities could be seen only with a microscope.

Prevention of Flashovers

The way of preventing flashovers is to avoid introducing microscopic irregularities in interfaces. A system which has been found highly immune to flashover consists of an unbroken dielectric film exposed through an aperture plate having a thickness of 1.5 mm. The opening is made with a cut perpendicular to the surface and the sharp corners are lightly smoothed. The interface for such a system is relatively free from irregularities and it remains free because flashovers to the aperture will erode aperture material without damaging the dielectric. In fact, the probability of flashover decreases with time for this type of interface. A coating of aluminum forms on the dielectric but apparently it does not degrade the performance of the interface. Joints in the aperture plate are undesirable as they may be a cause of flashover. However, not all joints were a problem and with further study, it should be possible to design joints which do not cause flashovers to occur.

Isolation of Specimen Areas

It is desirable to prevent a flashover on one area from spreading to other adjacent areas of dielectric. For two areas, each 19 by 25 mm, effective isolation was obtained with a metal barrier strip having a width of 4.8 mm. However, a 2.36 mm strip would allow the occasional spread of a flashover from one area to the other.

Recommended Testing

It is recommended to the sponsoring agency, which has large test facilities, that tests of flashover rate be conducted for specimens having a diameter of perhaps 20 cm. These would be constructed of 2-mil or 5-mil teflon exposed through 1.5 - mm aperture plates. One plate would simply expose the specimen through a single large aperture whereas others would be machined into a square grid, breaking the specimen surface into a number of small areas. Electrometers should monitor which segments loose their charges during a given flashover event.

ACKNOWLEDGEMENTS

The author is pleased to acknowledge the contributions of several students who have recorded much data and suggested many of the procedures and interpretations of the data. Scott Ehrenberg, Marc Gewertz, and Nguyen Nguyen are especially recognized for their assistance.

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FIGURES 1 - 21

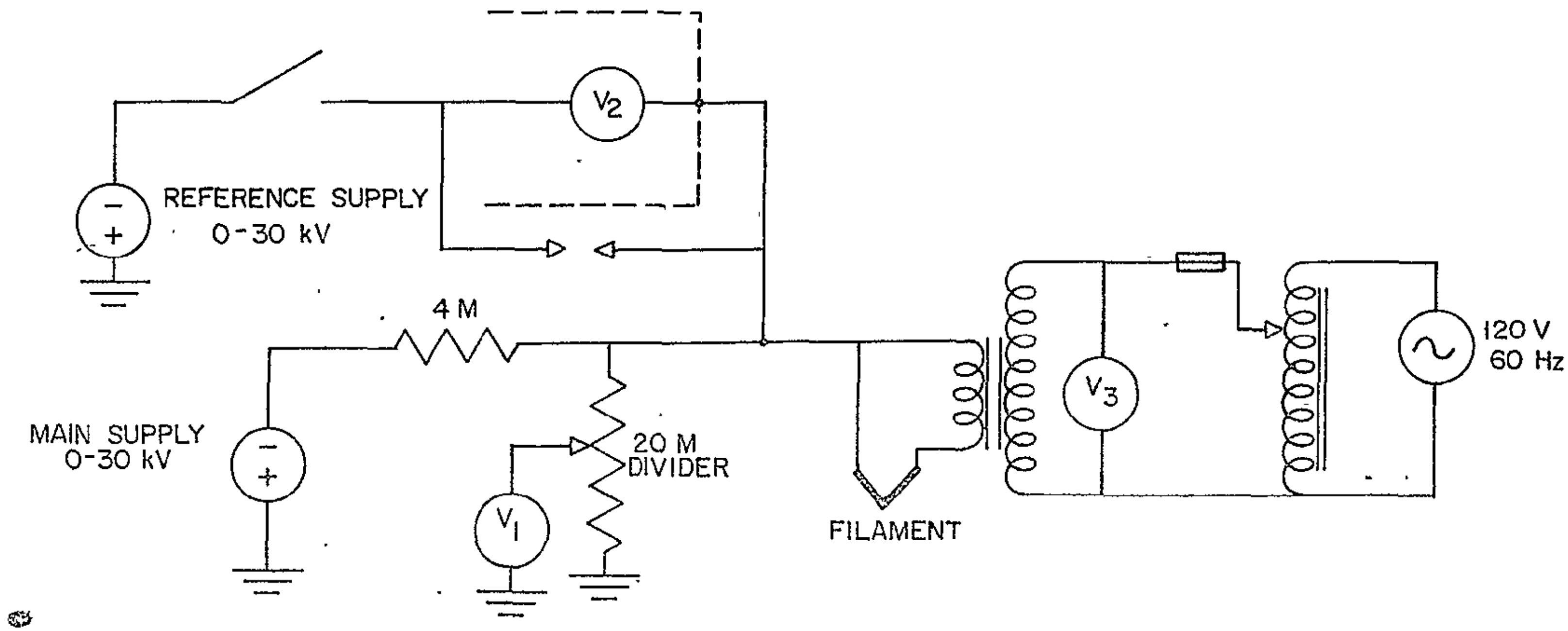


Fig. 1 Electrical circuit for controlling and measuring the parameters of the electron beam.

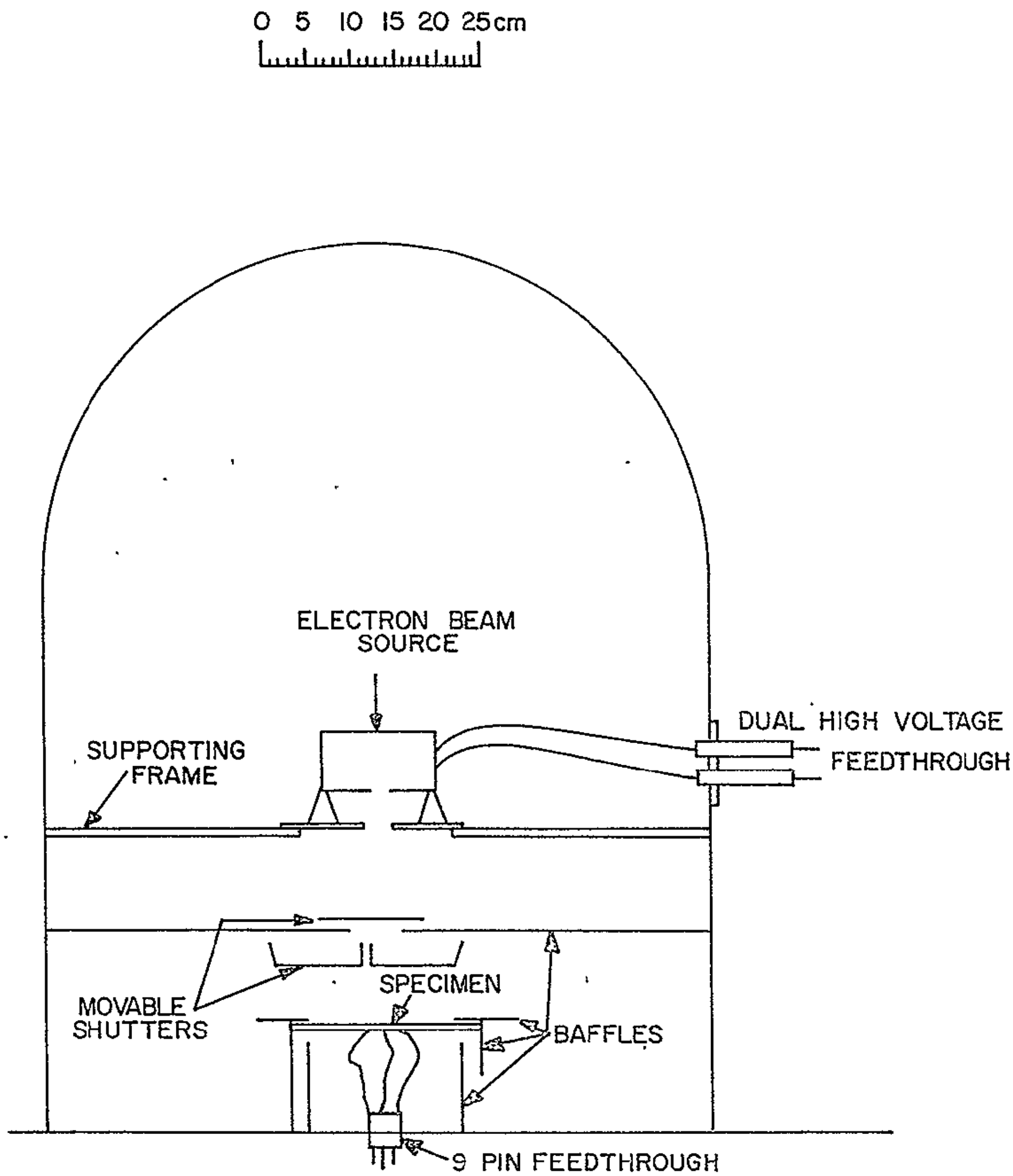


Fig. 2 Physical arrangement of components in the vacuum system. Not shown are mechanical feedthroughs which cause the shutters to move in horizontal planes.

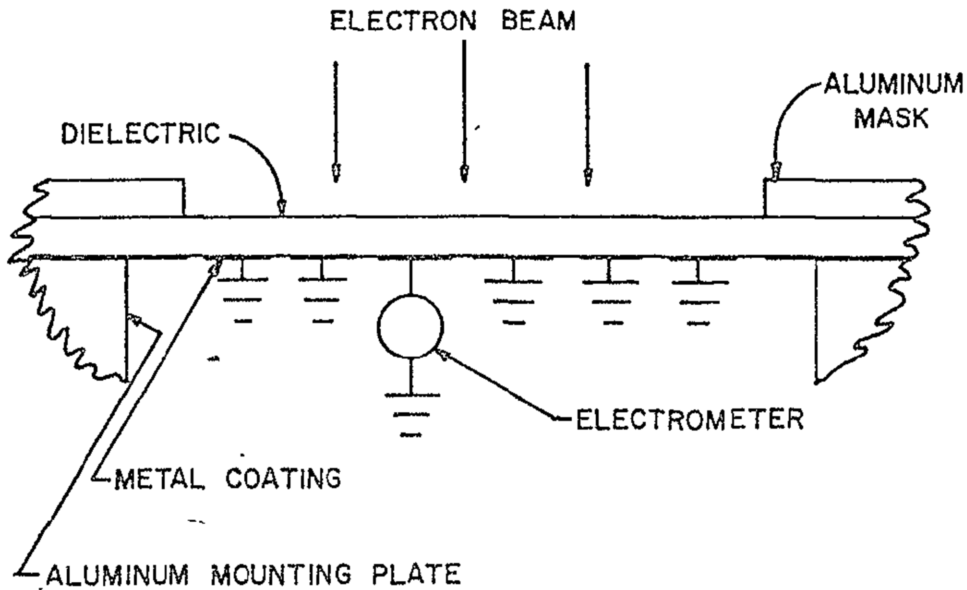
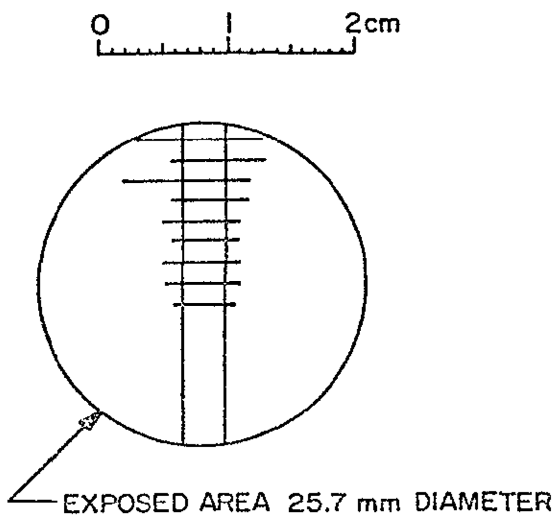


Fig. 3 Schematic illustration of the technique for measurement of surface charge. The dielectric film thickness is exaggerated for clarity.



SEGMENT	CAPACITANCE (pf)	DISTANCE d (mm)
1	.56	.6
2	.87	2.1
3	.72	3.8
4	.86	5.4
5	.88	7.1
6	.84	8.9
7	.86	10.4
8	.88	12.0
9	.80	13.8

Fig. 4 Line drawing made from a photograph of a specimen. The ladder structure, representing lines etched in the metal backing, is visible through the transparent dielectric film. Capacitances were measured by the water-drop method and d is measured from the edge of the aperture to the midpoint of a segment.

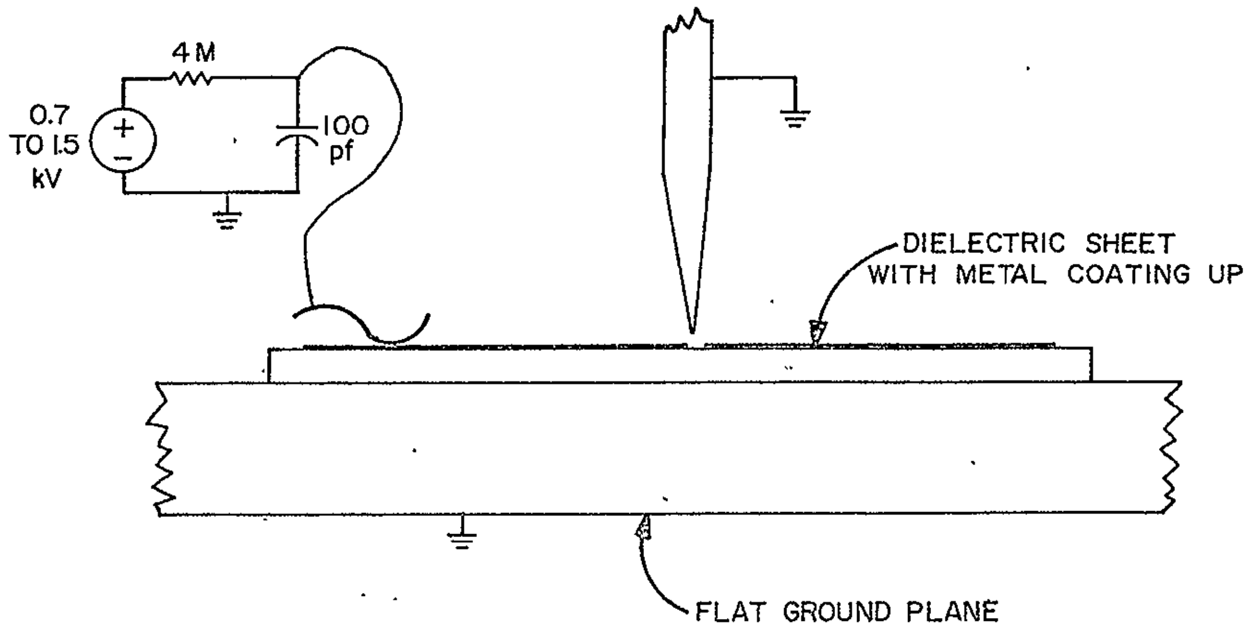


Fig. 5 Apparatus for machining lines in a specimen's metal coating. The point was attached to a carriage that allowed movement parallel to the surface.

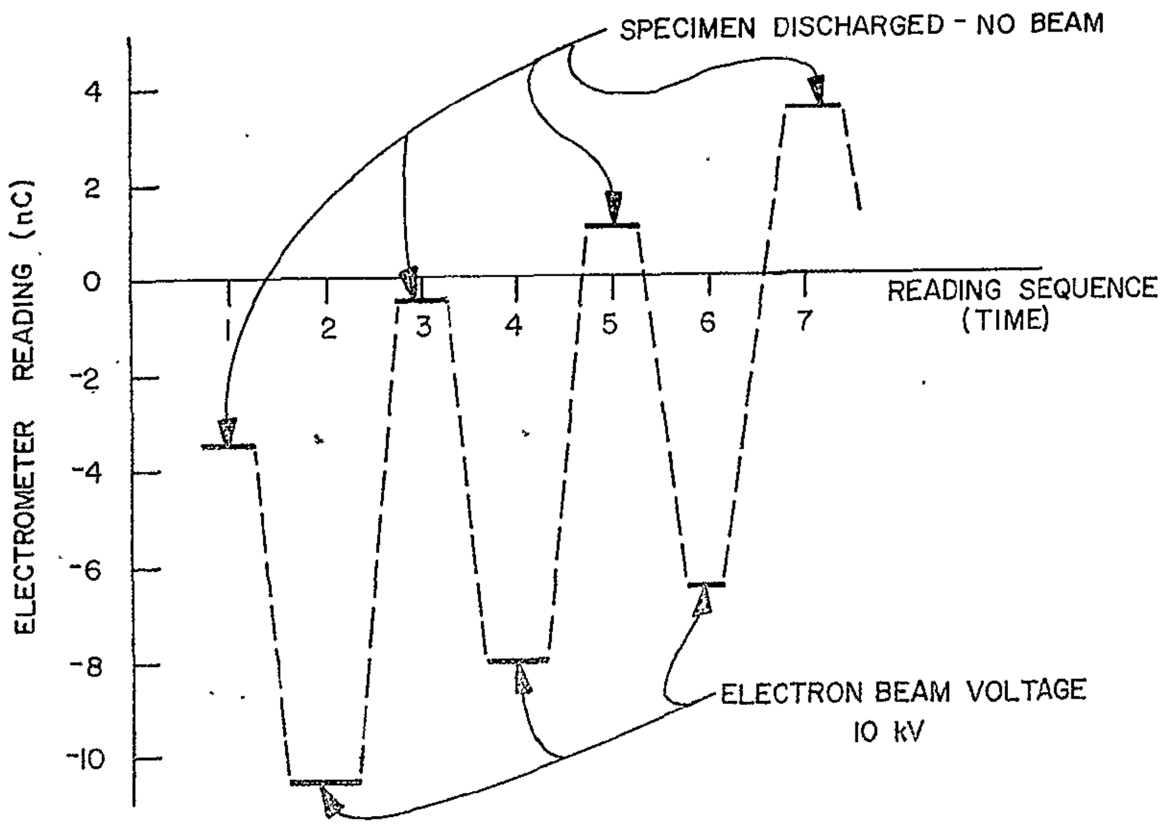


Fig. 6 Hysteresis of a segment as observed for a repetitive charging and discharging of the surface. In a voltage cycle there occurs a net transfer of charge to the electrometer whereas ideally there would be none.

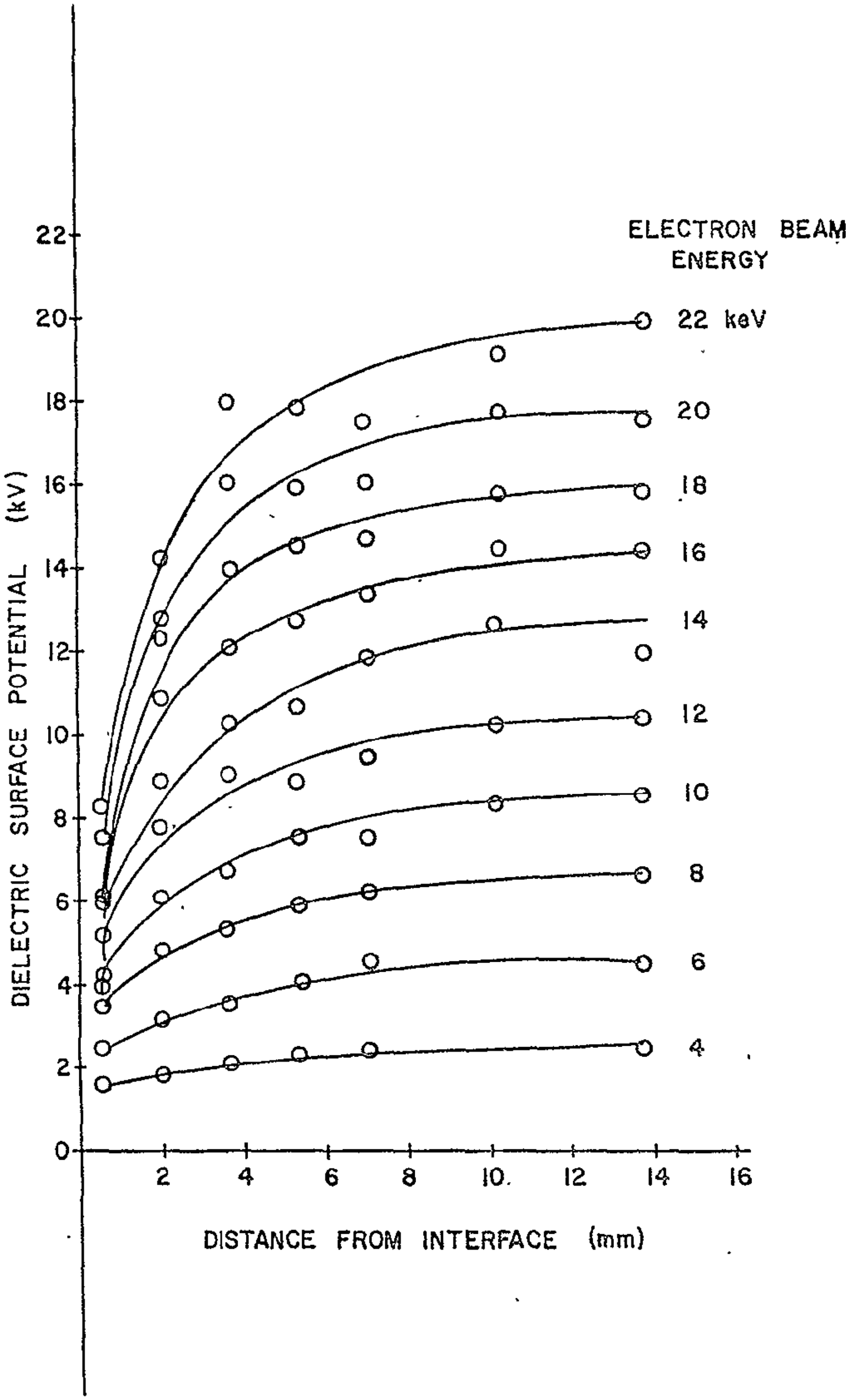


Fig. 7 Surface potentials of 5-mil FEP Teflon near the edge of an aluminum aperture plate. Points were determined from charge measurements and capacitances obtained from the water-drop method.

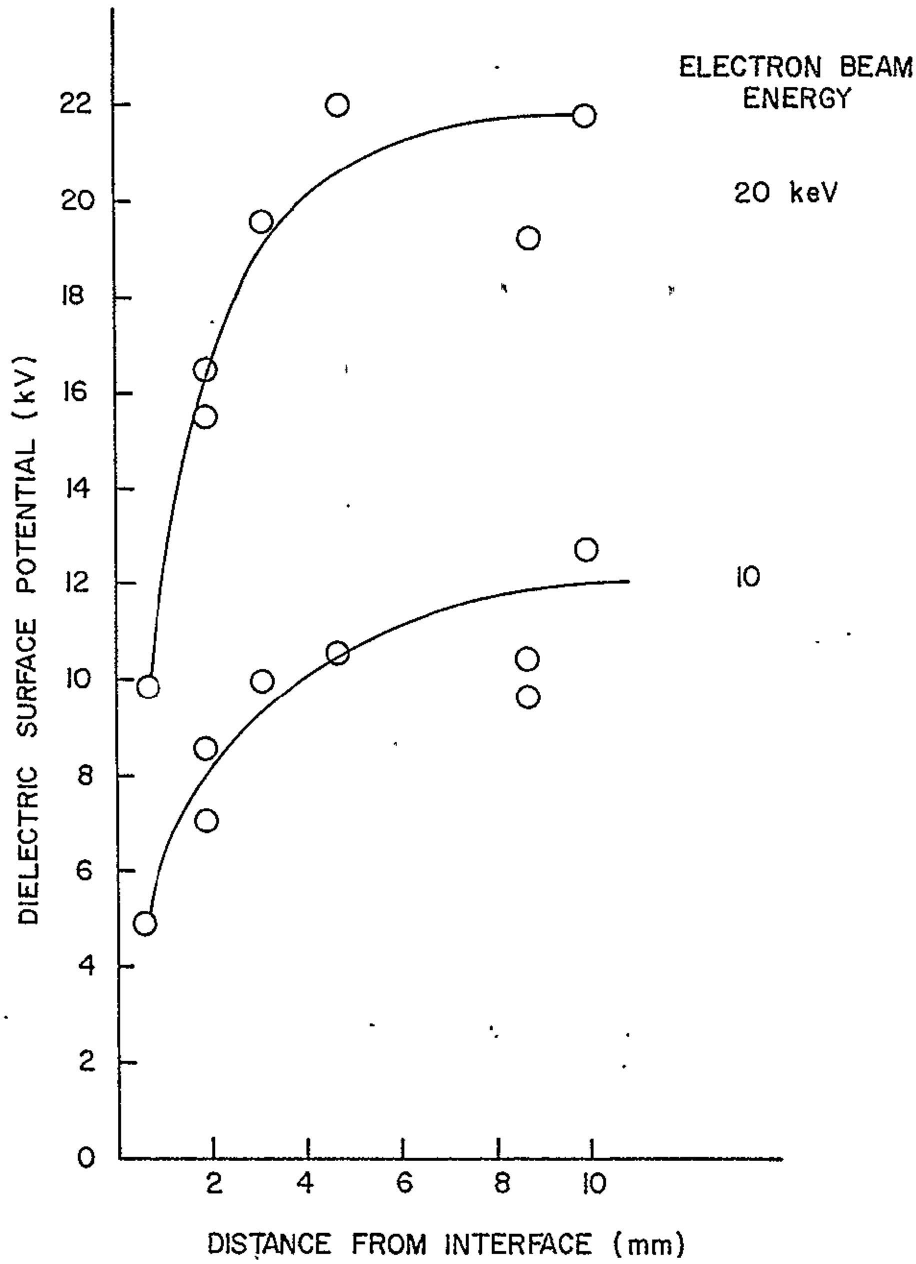


Fig. 8 Surface potentials of 5-mil Kapton obtained similarly to those of Fig. 7. The fact that potentials exceed the beam voltages is an indication of uncertainties in the data.

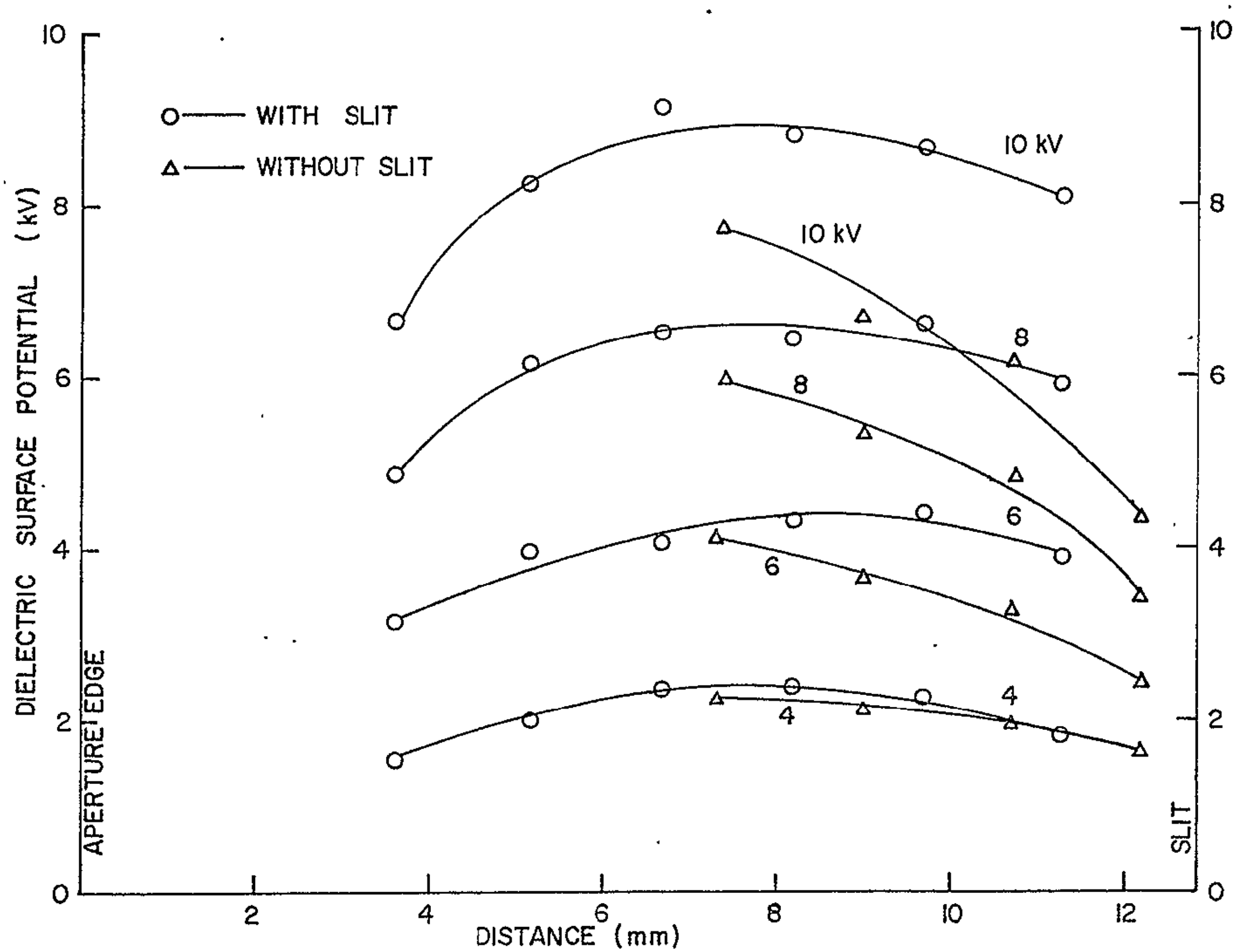


Fig. 9 A comparison of charge distributions near a slit and near an aperture edge for 5-mil FEP Teflon. The left margin is an aperture edge for the specimen with the slit. The data for the case of no slit is drawn such that the right margin

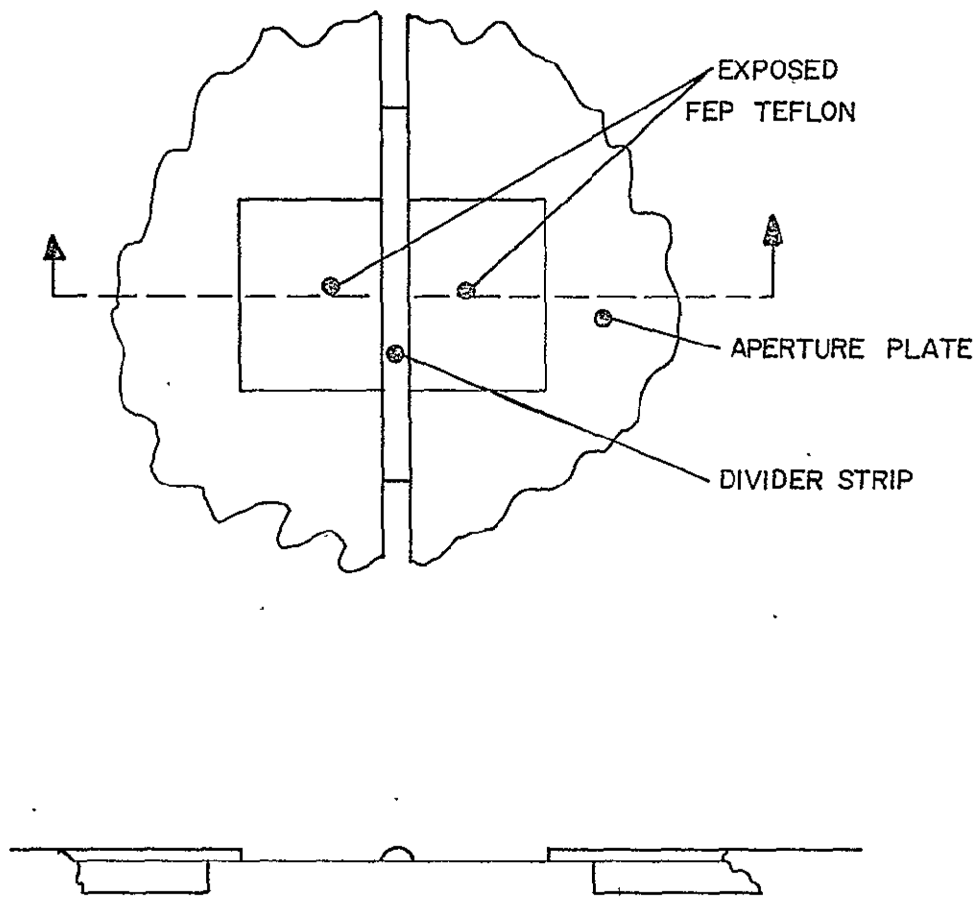


Fig. 10 Construction of a specimen with two exposed dielectric surfaces separated by a grounded metal barrier.

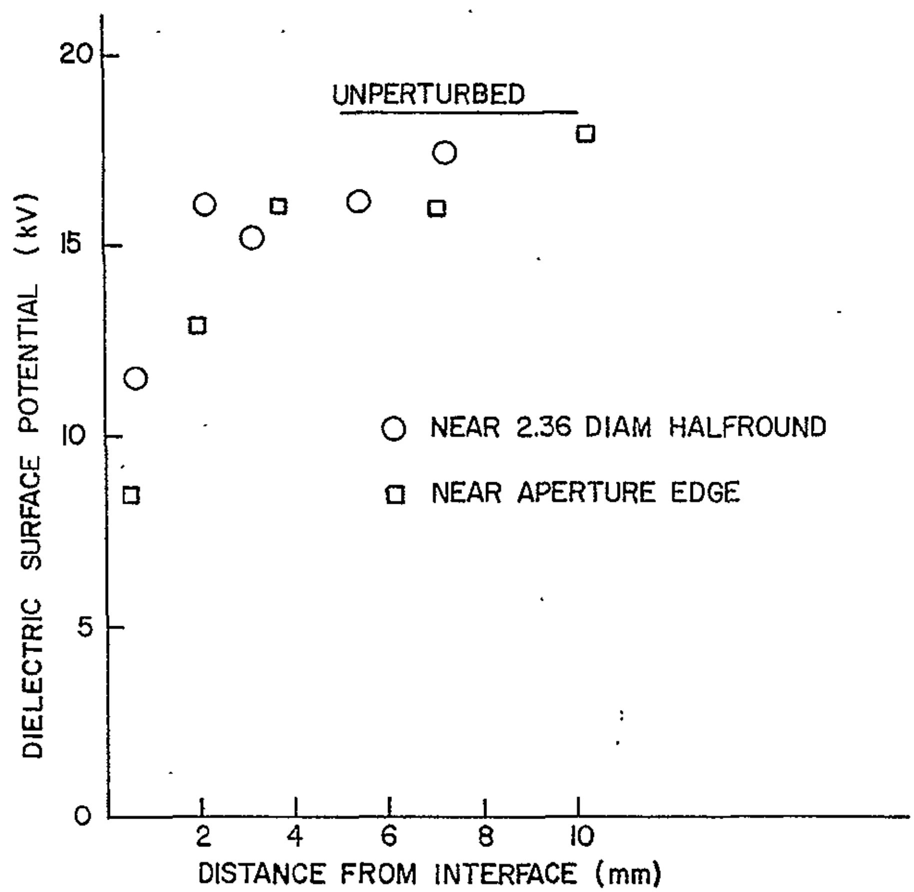


Fig. 11 A comparison of data points near a 2.36 diameter half-round divider strip and data points near an aperture edge for a 5-mil FEP Teflon specimen.

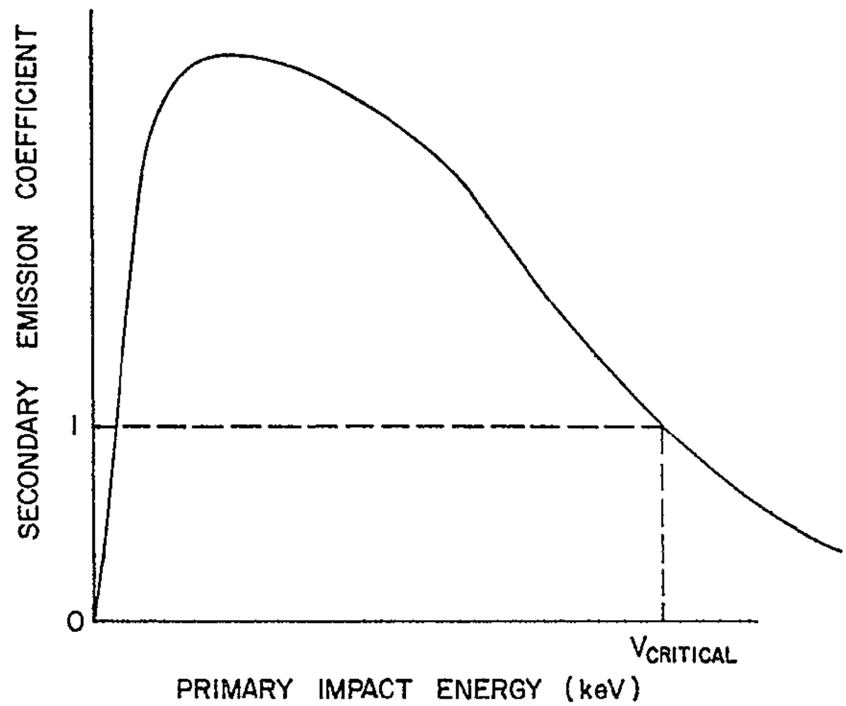


Fig. 12 Qualitative illustration of the secondary emission coefficient of a dielectric. The unity-crossover point is identified with the critical voltage and the peak is strongly skewed to the left.

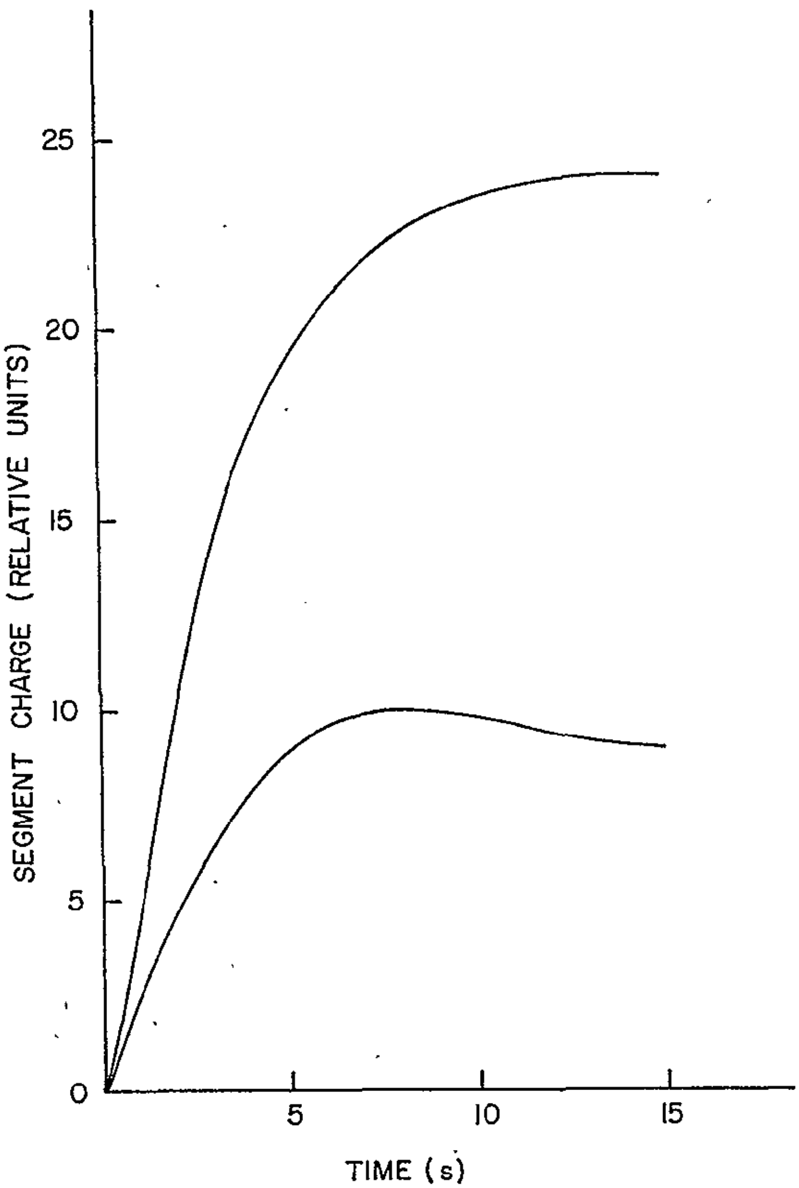


Fig. 13 Transient charging of two segments having more or less the same capacitance. The segment near an aperture edge overcharges and then loses charge as it approaches a steady state.

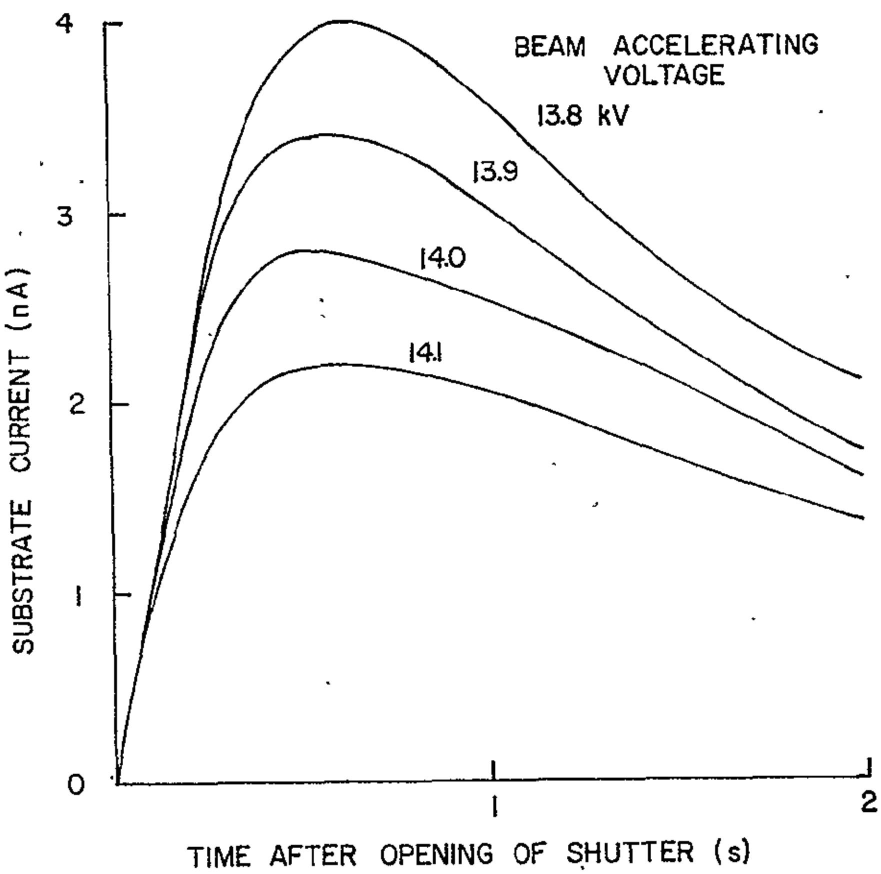


Fig. 14 Substrate current caused by a probing beam striking the specimen surface. The highest current corresponds to the peak of the secondary emission curve. A beam voltage of 13.7 kV produced no response in contrast to the curves shown above.

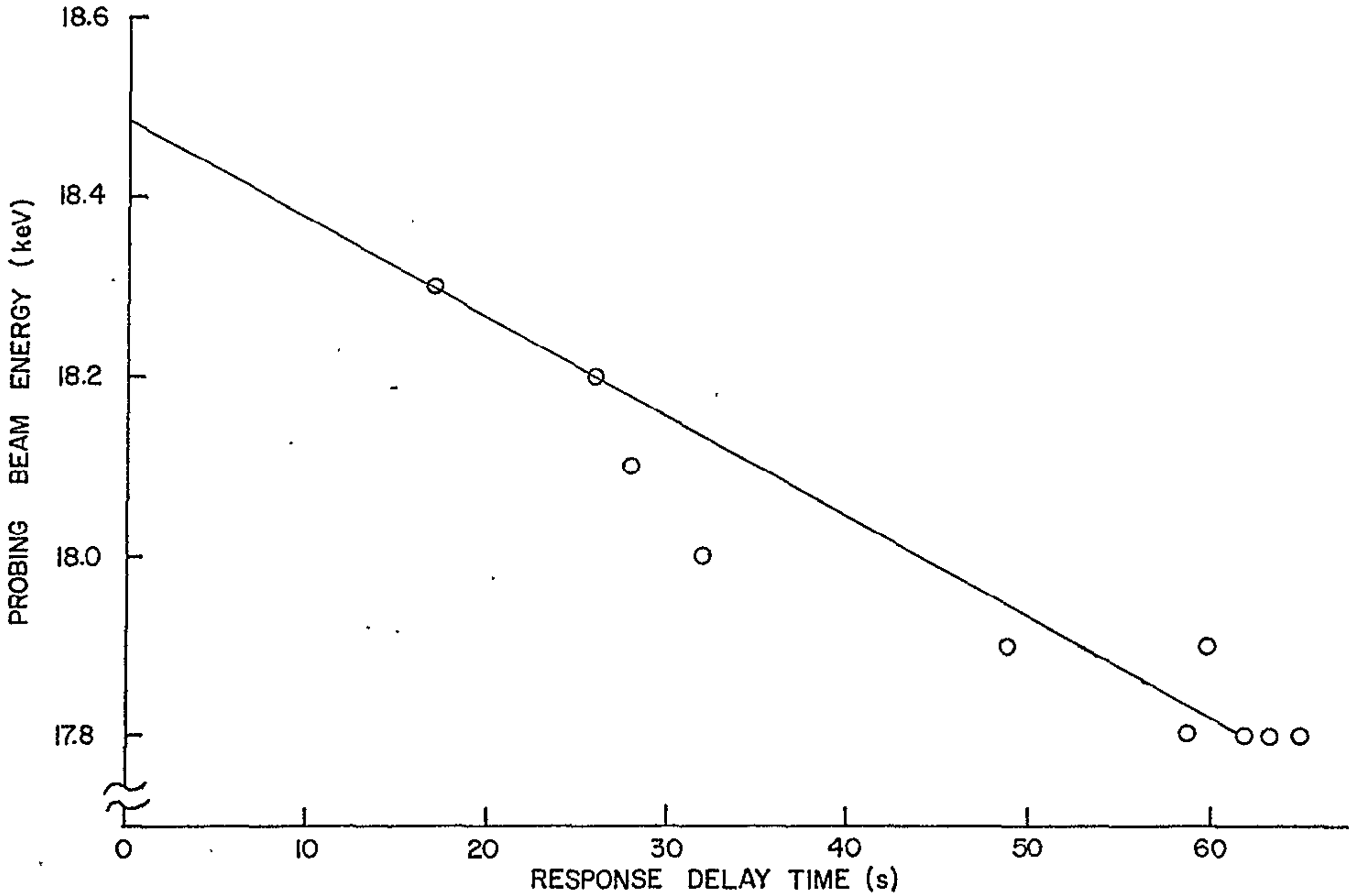


Fig. 15 Decay of surface potential on a 2-mil FEP Teflon specimen after several days in vacuum.

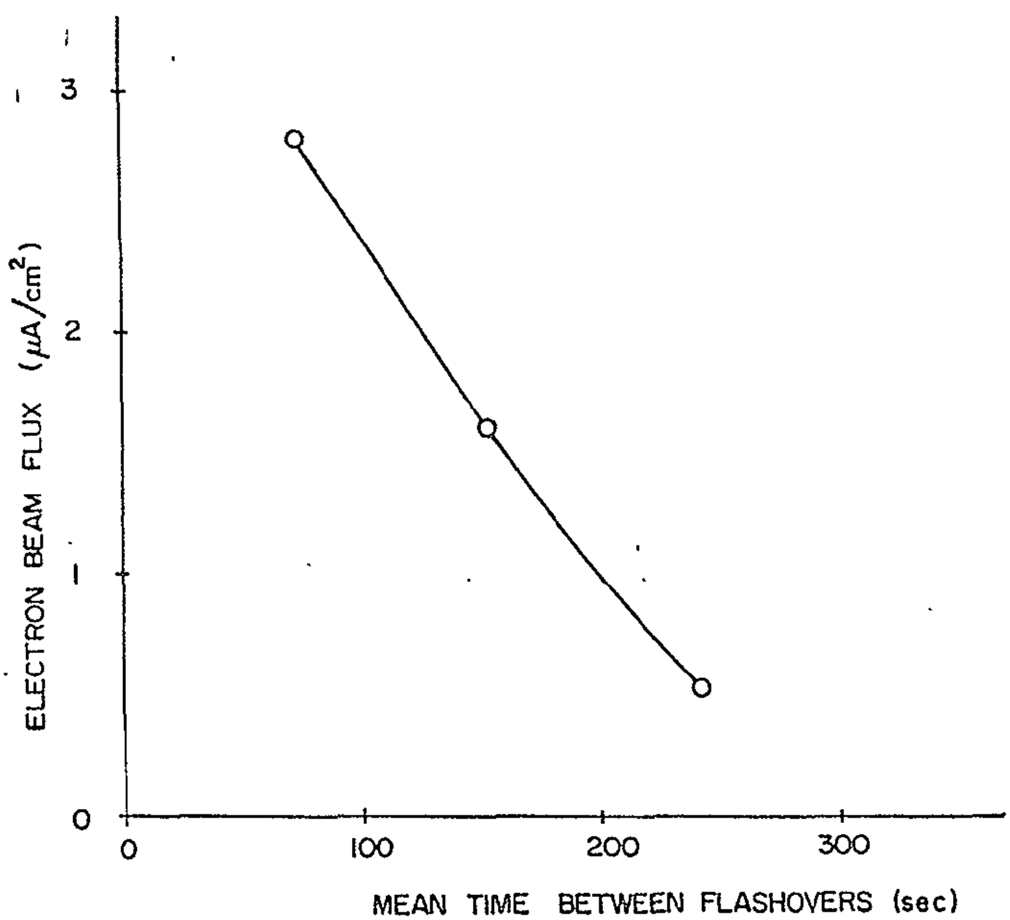


Fig. 16 Flashover data for a 5-mil FEP Teflon specimen exposed to a 21 keV electron beam.

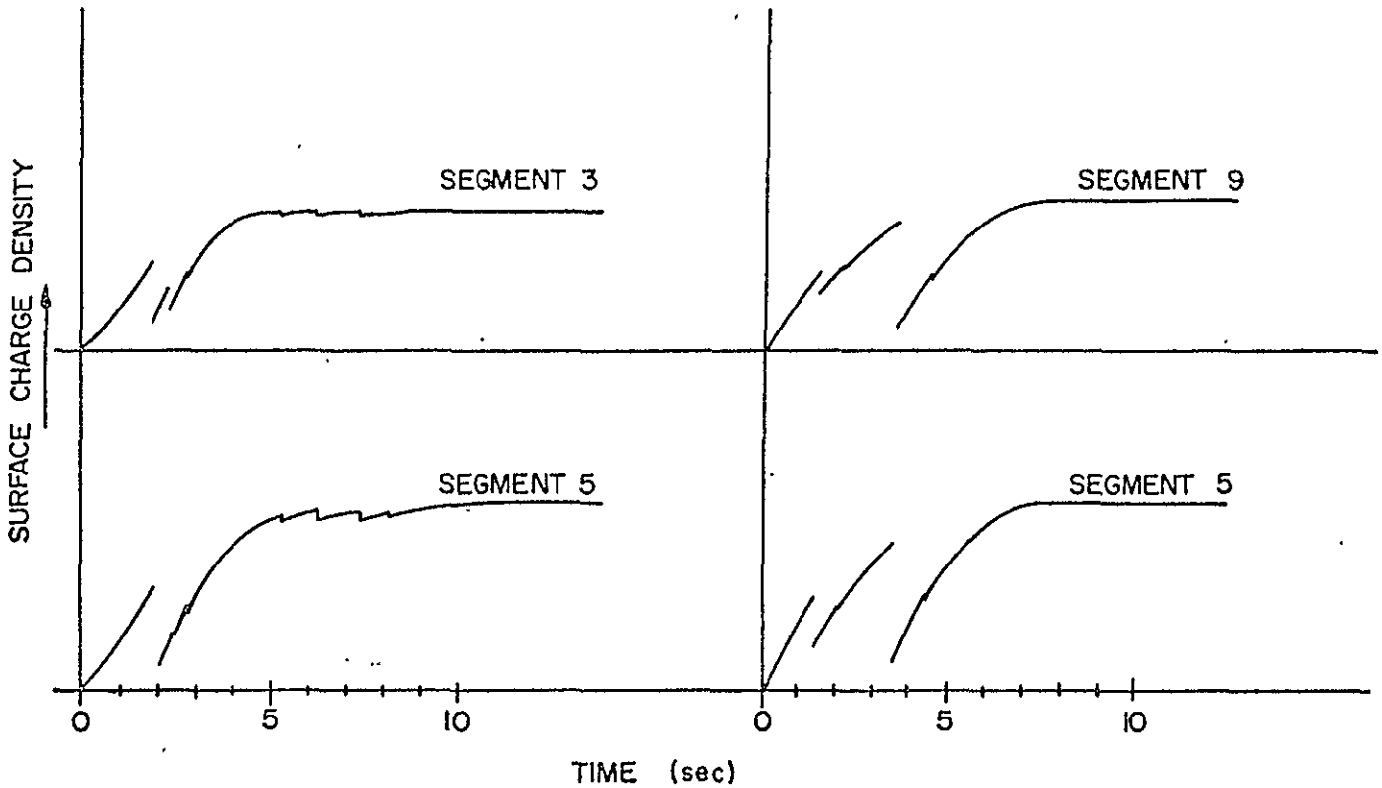


Fig. 17 Partial flashovers during charging transients for a 5-mil FEP Teflon specimen with an aperture plate having a thickness of .076 mm.

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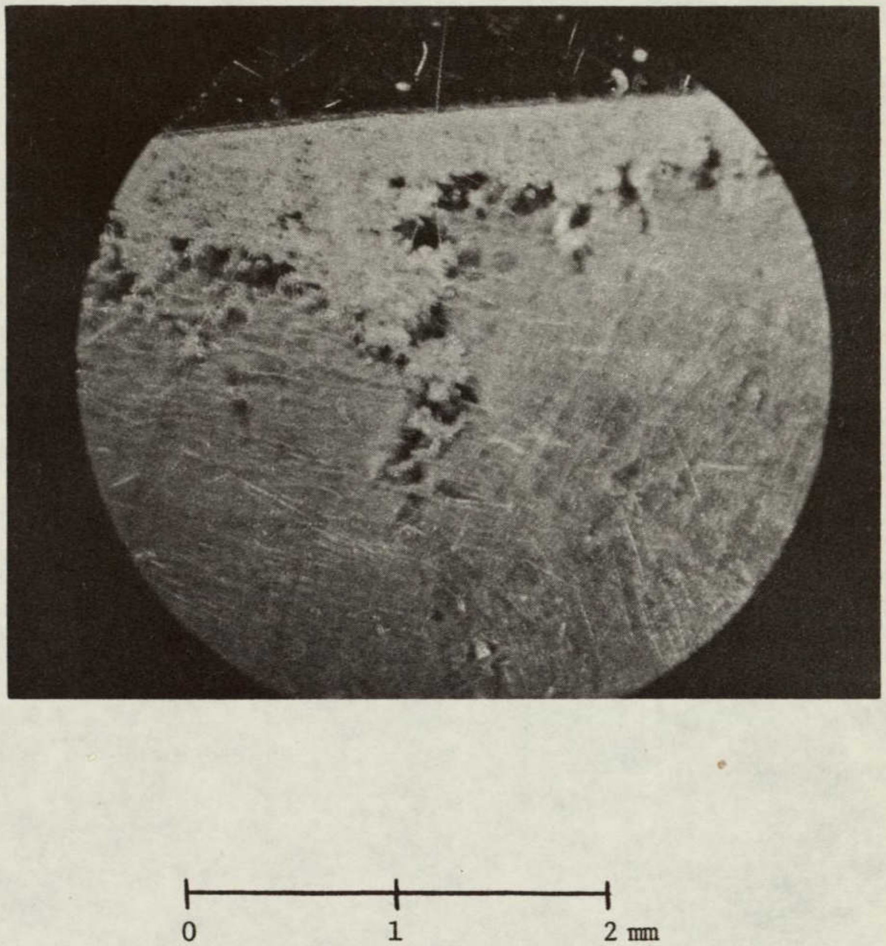

Fig. 18 Coating on FEP Teflon near the edge of the aperture plate. The dark region is where the plate had covered the specimen. Also, one can see a gradual darkening (or thinner coating) in the background as the point of interest moves away from the aperture plate. Large splotches of coating are superimposed on a relatively uniform background coat.

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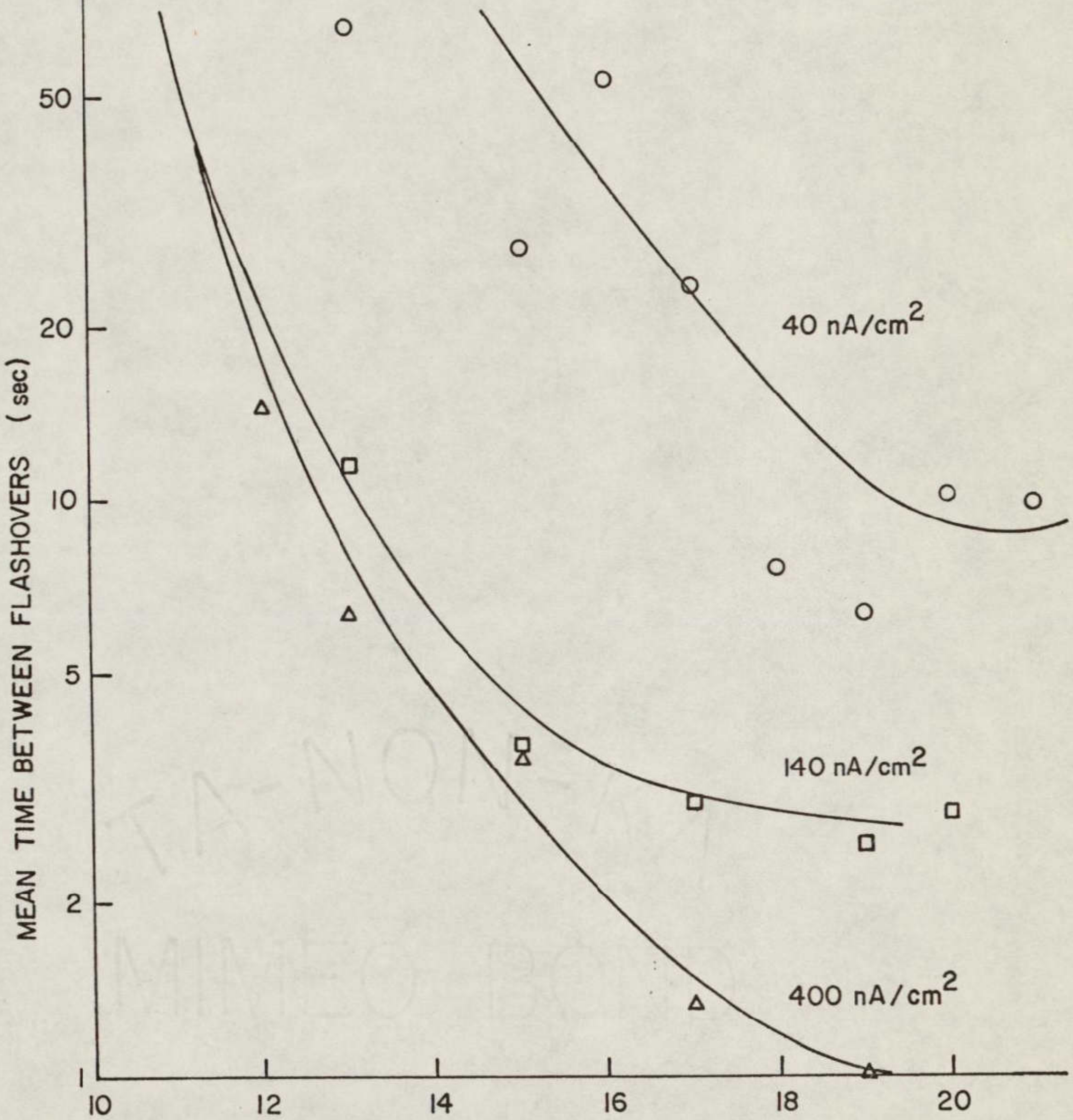

Fig. 19 Mean time between flashovers for a 5-mil FEP Teflon specimen with a slit. Epoxy was applied after the slit was cut.

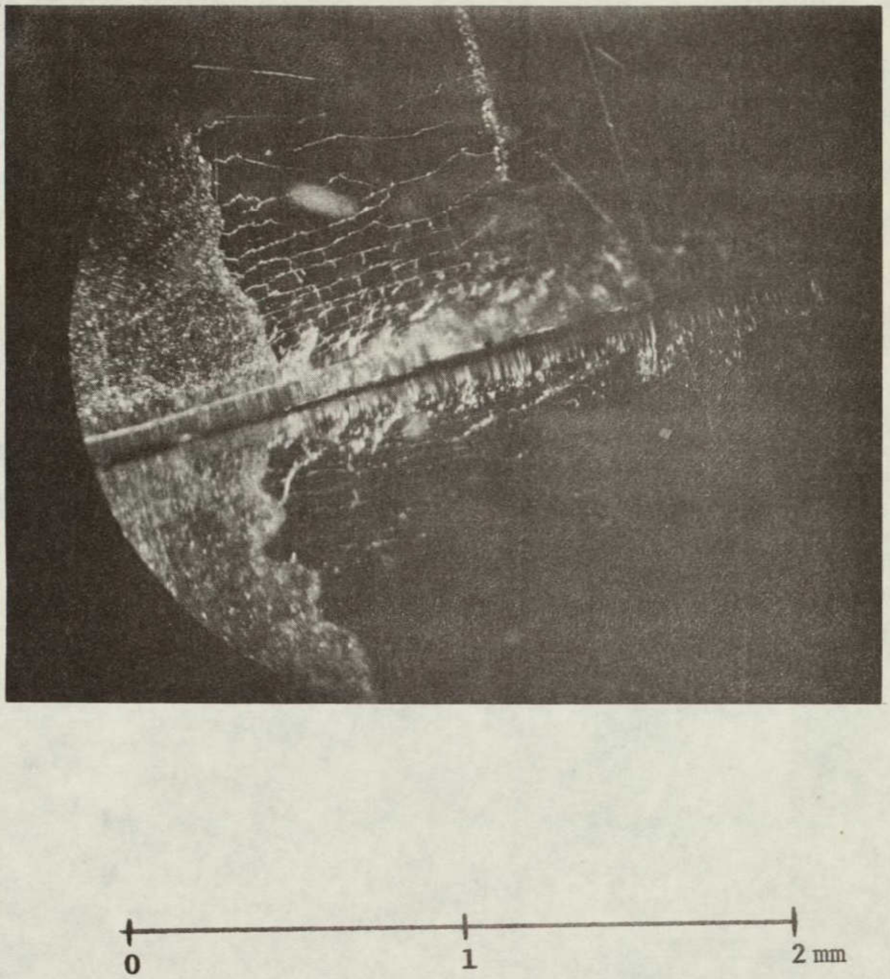

Fig. 20 Enlarged photograph of a slit in 5-mil FEP Teflon showing a bead of conductive epoxy that has oozed through the slit.

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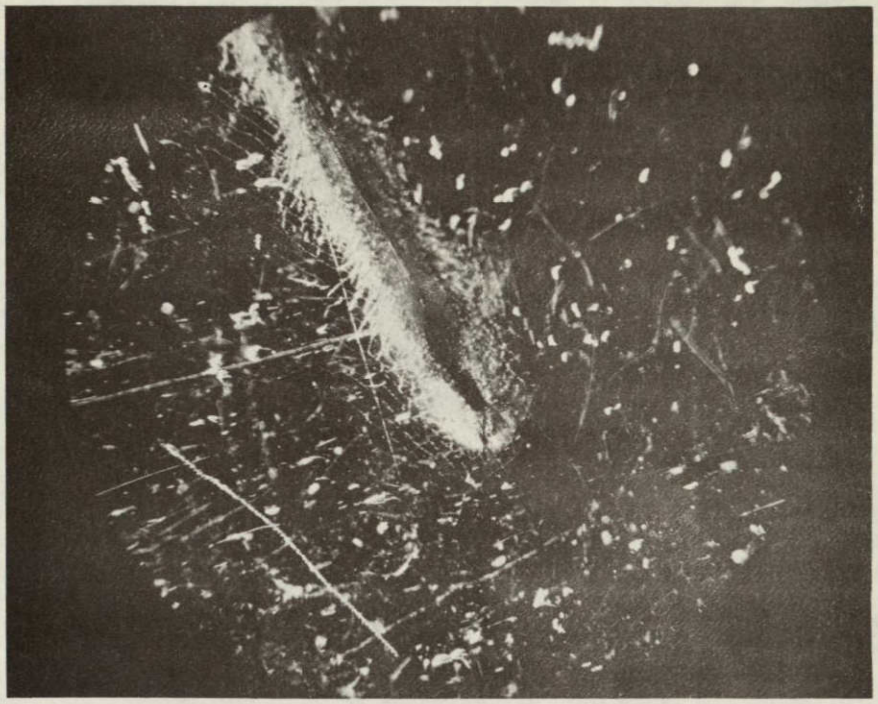

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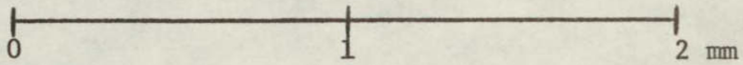

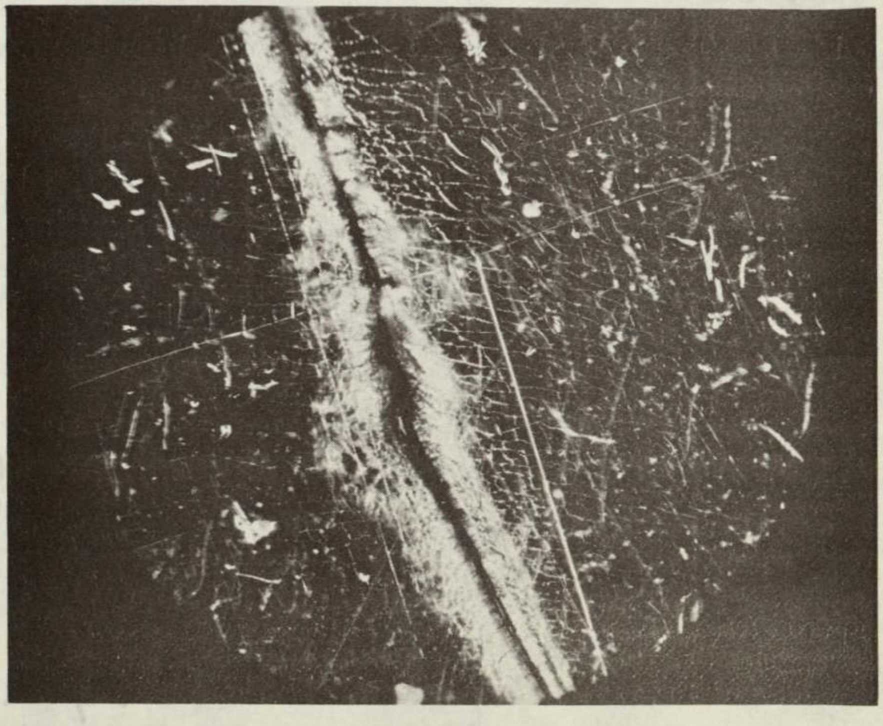

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Fig. 21 Points of dielectric erosion along a slit in a 2-mil specimen of FEP Teflon which has experienced numerous flashovers.